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PYROMETRY

PYROMETRY

BY

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PREFACE

Industrial developments during the last quarter century have made the accurate measurement of temperature one of the most important phases of the processes involving the production or application of heat. In many plants the entire time of one or more skilled technicians is occupied in maintaining the pyrometric system. This condition has been reflected in colleges and universities by the establishment of separate courses in temperature measurement. Such courses are usually offered by the Engineering or Physics departments.

While there are a few reference books on pyrometry there is no work which is organized in such a manner as to be of great utility as a textbook for college students. Instructors have been forced to handle the subject entirely by lecture or by personally prepared sets of notes. This manuscript, therefore, has been assembled with the needs in mind of the student as well as of the man more experienced in the uses and the theory of pyrometry. Questions and problems are added at the end of some of the chapters. Outlines for laboratory experiments are included. These are largely suggestive and may be modified to meet local conditions.

We wish to express our great appreciation for the assistance which has been rendered by the manufacturers of pyrometric equipment and others in the preparation of this manuscript. The publications of the U. S. Bureau of Standards have been drawn upon freely, particularly, *Technologic Paper* 170. Other references to be mentioned are "Dictionary of Applied Physics," Glazebrook, Volume 1; "The Measurement of High Temperatures," Burgess and Le Chatelier; "Temperatur Messung," Henning; "The International Critical Tables;" and the three symposia on pyrometry, the first held by the British Iron and Steel Institute in 1904, the second by the Faraday Society in 1917, and the third by the American Institute of Mining and Metallurgical Engineers in 1919. Wherever tables or illustrations have been used from these sources the name is appended.

Especial thanks are due our colleagues, Profs. A. H. White, C. Upthegrove, and G. G. Brown for helpful criticism of various parts of the manuscript.

THE AUTHORS.

ANN ARBOR, MICHIGAN,
August, 1927.

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PYROMETRY

CHAPTER I

TEMPERATURE SCALES

Temperature.—Purely mechanical phenomena may be completely described in terms of three quantities, considered by agreement as fundamental, such as mass, length, and time. To describe those phenomena involving heat, it becomes necessary (aside from the kinetic theory) to introduce a new fundamental quantity. Such a quantity is temperature. Since the knowledge of the properties of matter can only be gained through sense perception, every fundamental quantity must ultimately be defined in terms of certain received sensations. The temperature of a body may thus be qualitatively defined as the property of a body which determines the sensation of warmth or coldness received from it. Experience shows, however, the inadequacy of the sense organs in quantitative measurements. The same body might be regarded as either warm or cold, depending upon the circumstances of observation. It therefore becomes necessary to adopt by agreement some device for obtaining a quantitative expression of temperature.

Heat.—Having defined temperature, it becomes easy to define heat, regardless of its ultimately true nature. Thus heat may be spoken of as that something (form of energy) which, if present in a body in larger quantities, results in more acute sensations of warmth or higher temperatures. Observation readily shows that along with the more acute sensation of warmth, there is a marked change in all of the other physical properties of the body. Among these changes the following might be noted in particular:

1. Increase in dimensions.
2. Increase in pressure, if confined.
3. Change in e.m.f. developed when in contact with some other substance.
4. Change in electrical resistance.
5. Increase in the amount of radiation from the surface of the body.
6. Change in color of the body.
7. Change in state.

Many of these changes are accurately measurable and any one of them might be used by agreement as a measure of the accompanying temperature change and, hence, be the basis of a temperature scale. As a matter of fact, every one of the changes noted above has been used at some time or other as the basis of temperature scales. It must be noted, however, that inasmuch as they employ different properties of the substance, temperatures measured upon one scale should not necessarily agree with the same temperatures measured upon a different scale. Only on that scale accepted by agreement would the temperatures be correct.

It would, of course, be desirable to obtain a temperature scale which was independent of the particular properties of any substance. Such a theoretical scale was proposed by Lord Kelvin, and it may be approximately attained in practice. This thermodynamic scale will be discussed later.

Thermometry by Quantities of Heat.—A system of thermometry might be founded upon the measurement of quantities of heat rather than upon the change in some physical property of a substance, although this method would be found rather inconvenient. Thus, if any two definite temperatures be agreed upon as fixed points such as the freezing and boiling points of pure water under standard conditions, the unit of heat may be taken as the quantity of heat needed to raise the temperature of a certain unit of mass of water from one of these temperatures to the other.

For convenience this unit of heat may be related to the quantity of heat needed to melt unit mass of ice at the lower fixed temperature. Now the temperatures of two bodies of the same mass and material may be considered as being proportional to the quantities of ice melted by each when dropped into an enclosure of ice at its melting point. To affix definite numbers to the temperatures, the dropped body must in one case be given an initial temperature equivalent to that of the higher fixed point. If this be called 100 as in the Centigrade scale then the other temperatures may be directly evaluated. This method, of course, assumes that the specific heat of the test body is constant at all temperatures, which is not true for any substance. This method of mixtures used in connection with mercury thermometers was, however, one of the very early methods of estimating the temperature of very hot bodies.

Temperature Measurement by Secondary Standards.—As will be described later, the fundamental measurement of temperature depends upon an international agreement regarding a constant-volume gas thermometer, together with the two fixed temperatures, the freezing and boiling points of water under standard conditions. By painstaking experimentation with this device, the melting and boiling points of many substances from the boiling point of helium ($-268.8^{\circ}\text{C}.$) to the melting point of palladium ($1553 \pm 3^{\circ}\text{C}.$) have been evaluated. These established definite temperatures may then be regarded as fixed points on an equal basis with the two original fixed points. In carrying out actual temperature measurement in the above temperature range and beyond, the constant-volume gas thermometer is unwieldy and many other secondary devices are used. These may be calibrated by means of the established fixed-temperature points. The type of secondary device used is determined by the temperature range to be covered. For the range from the very lowest temperatures possible up to $1500^{\circ}\text{C}.$, noble-metal thermocouples may be used. For the range -40 to $1100^{\circ}\text{C}.$, resistance thermom-

eters of platinum may be used satisfactorily. Above 700°C., temperature-measuring devices, based upon the radiation laws, may be employed. These devices, when calibrated by the fixed points established by the gas thermometer, may be used to higher temperatures by extrapolating the scale law discovered for them at the lower temperatures.

Accuracy in Temperature Measurement.—The magnitude of the error present in the evaluation of a high temperature may be appreciable. In the first case, all measurements depend upon the correctness of the value of the fixed points employed in calibrating the indicator. That these points are not always certain may be illustrated from the fact that in the case of the sulphur boiling point, values have been assigned by observers using the gas thermometer from 443.7 to 444.7°C. At higher temperatures, the discrepancy increases so that in the case of the melting point of palladium values range from 1549 to 1556°C. In this case, it becomes necessary to make a choice of a preferred value. At very high temperatures, the uncertainty is greatly magnified. The radiation laws which underlie the operation of both optical and radiation pyrometers were originally based upon experiments by Lummer and Pringsheim¹ regarding the radiation from a black body whose temperature was measured by thermocouples.

This work was performed before the best work in establishing the high-temperature scale (Day and Sosman)² had been carried out. To this uncertainty of the constants of the radiation laws and that of errors in the fixed points, the uncertainty in extrapolating a law beyond the limits for which the law was verified is added. Hence, in the case of the melting point of tungsten, the value may be given as $3380 \pm 20^\circ\text{C}$. The melting point of graphite has been reported as $3600 \pm 100^\circ\text{C}$.

By making assumptions regarding the value of certain fixed points together with the value of the constant in the radiation law,

¹ *Wied. Ann.*, vol. 63, p. 395, 1897.

² *Carnegie Inst. Pub.* 157, Washington, 1911.

different standardizing laboratories are able to agree to a great extent at the present time on a high-temperature scale.

The ability to reproduce readings with a given instrument is a matter of importance. This has been accomplished in many instruments by remarkable improvements in design. As an illustration in the case of the disappearing-filament optical pyrometer, Fairchild and Hoover¹ by eliminating diffraction effects, etc. report a reproducibility of readings at the melting point of gold 1063°C. of 0.2°C. or better.

¹ *Jour. Optical Soc. Am.*, vol. 7, p. 543, 1924.

CHAPTER II

FLUID THERMOMETERS

Fluid thermometers include all the types of instruments which indicate variations in temperature by means of a measurable change in volume or pressure of a fluid held in a gastight container.

Mercury in Glass Thermometers.—The earliest devices for comparing temperatures made use of the change in volume of a confined fluid as it was being warmed. In the first instruments used in the early part of the seventeenth century, the expansion and contraction of air was used as an indication of the temperature. The introduction of mercury together with the use of enlarged bulbs is attributed to Fahrenheit in the early part of the eighteenth century. His scale was based upon three quite arbitrary, fixed points, namely: the temperature of a certain mixture of ice and salt was taken as 0, that of a mixture of ice and water as 32, and that of the human body as 96. On this scale, the temperature of boiling water was found to be 212, although this was not used as a reference point. The numbers 32 and 212 are retained on the modern Fahrenheit scale. More accurate observations show the temperature of the human body to be 98.6 instead of the value 96 assigned to it by Fahrenheit. In measuring temperatures by an instrument of this sort, it is evident that the underlying assumption is as follows: Those changes in temperature, which produce equal apparent changes in the volume of a given amount of mercury enclosed in a glass container, shall be considered equal temperature changes.

It is remarked that Réaumur, in warming a mixture of alcohol and water from the freezing point to the boiling point, found an increase in volume of 80 parts in 1,000. He consequently divided his scale into 80 divisions, taking 0 as the freezing point. This

scale, applied to mercury thermometers by other observers, gives the present Réaumur scale in common use in certain countries and in certain industries.

In the Centigrade scale, whose origin is attributed to Celsius, the values of 100° and 0° were assigned, respectively, to the freezing point and boiling point of pure water. These numbers were

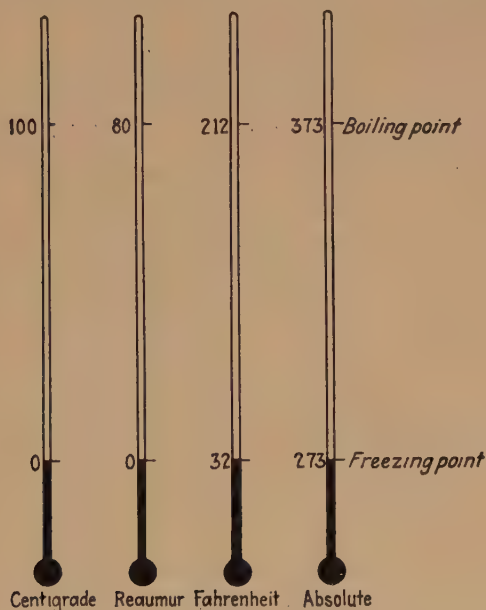


FIG. 1.—Fixed points on the various temperature scales.

later inverted, giving the present Centigrade scale. A certain temperature may thus be expressed in the three scales, as follows:

$$T_c = \frac{5}{9}(T_f - 32) = \frac{5}{4}T_r,$$

where the subscripts of T denote the corresponding scale readings. Figure 1 shows the numbers assigned to the two fixed points on the various scales.

The properties of mercury make it a very desirable thermometric substance when used in a glass container. Being a liquid, the change in volume of a large volume of mercury in the bulb, induced by a slight temperature change, may be confined to the

capillary stem, and made readily apparent. The volume coefficient of expansion of mercury is large and fairly uniform when expressed in terms of the fundamental scale to be described later. Its low freezing point -40° and high boiling point 356°C. which may be extended further by added pressure, make a fairly wide working range. It is not compressible and its surface tension is such that it does not adhere to the glass. It is readily observable due to its high reflecting power. To extend the upper range of the thermometer beyond 356 , the stem of the thermometer may be filled with nitrogen and sealed at a low temperature. The increasing volume of mercury compresses the nitrogen and raises the boiling point of the mercury. At sufficiently high temperatures, however, the glass will soften and become stretched, due to the high pressure. By using quartz containers, the upper temperature limit may be extended to 650°C.

Glass suitable for thermometers should possess certain characteristics. A thermometer made and calibrated, using freshly blown glass, is found to develop scale errors after a time, due to the shrinkage of the glass. Bulbs are therefore aged until the final, constant volume is attained before they are filled. Most glasses show a hysteresis effect; that is, upon being heated and subsequently cooled to the starting temperature, they do not regain their original volume completely at once, but are left slightly enlarged, giving a depression of the freezing point.

Other Liquid Thermometers.—For use at higher temperatures, thermometers of this type have been constructed, employing liquid tin as the fluid in a container made of porcelain or platinum. With opaque containers, the scale may be read by lowering a scale from the top to make contact with the top surface of the molten tin. For temperatures below the freezing point of mercury, the bulb may be filled with toluol, alcohol, or pentane, the freezing points of which are, respectively, -97°C. , -113°C. , and -200°C.

The Gas Thermometer.—While the liquid in the solid-container type of thermometer is convenient to use, still, due to the

relatively large coefficient of expansion of the container compared to the fluid and the limited working temperature range, thermometers of this type have not been adopted as fundamental in temperature measurement. If a given amount of gas be enclosed in a bulb, the temperature of which is raised and the volume of the gas kept constant, its pressure will increase.

If the pressure of the gas be kept constant, its volume will increase. This change in volume of the gas compared to the change in volume of the container for the same temperature change is very large. For various reasons, it was agreed at a meeting of an International Committee on Weights and Measures in 1887 that the former of these changes when taking place in an apparatus set up under certain prescribed conditions should serve as the fundamental temperature-measuring device. This may be called the "normal hydrogen thermometer." Figure 2 shows a constant-volume gas thermometer. In the normal hydrogen thermometer, the gas used is hydrogen and the pressure of the gas at $0^{\circ}\text{C}.$ was prescribed as 100 centimeters of mercury.

For certain ranges of temperature, it becomes desirable to use different gases and different pressures at the freezing point, but these may be calibrated directly with the normal thermometer over that part of the range so that both may be used. Thus, at high temperatures, it is difficult to obtain a container that is impervious to hydrogen and for this work nitrogen is substituted. The pressure at $0^{\circ}\text{C}.$ is commonly taken as 50 centimeters of mercury in order that the pressure at high temperatures may be correspondingly reduced. For low temperatures helium is used, since it remains a gas at a temperature at which the hydrogen has liquified.

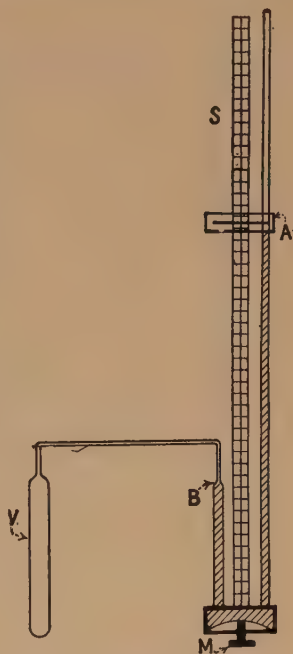


FIG. 2.—Constant-volume gas thermometer.

The fixed temperatures for the normal thermometer were agreed upon as the boiling and freezing points of distilled water under standard conditions. It is thus evident that the scale law of this device may be stated as follows: Those changes in temperature that produce equal changes in the pressure of a given amount of hydrogen in glass are equal temperature changes. Thus, a curve in which pressure is plotted against temperature should appear as a straight line, as shown in Fig. 3. To calibrate the thermometer,

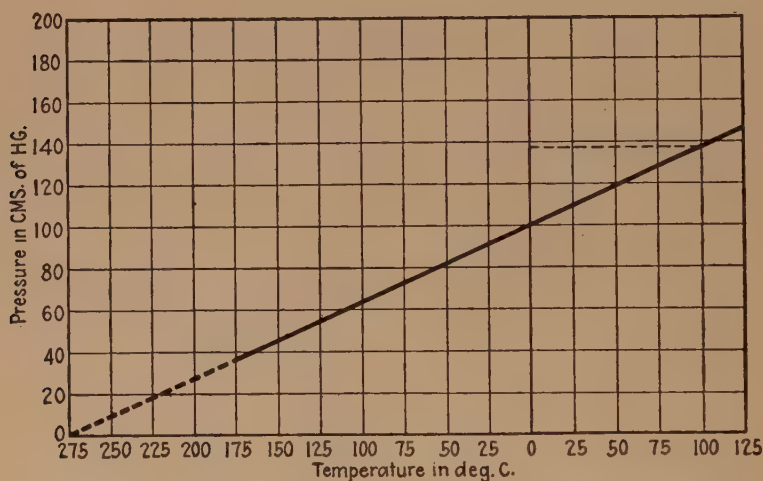


FIG. 3.—Pressure temperature relationship in normal thermometer.

its pressure is adjusted to 100 centimeters of mercury when the bulb is placed in melting ice and this value of pressure designated P_0 . The bulb is now placed in a steam bath under standard conditions, and the pressure P_{100} measured when the volume is adjusted to the original value. The pressure change per degree a is then

$$a = \frac{P_{100} - P_0}{100}. \quad (1)$$

To measure an unknown temperature x , the pressure corresponding to it, p_x , is measured. Then x is given by

$$x = \frac{P_x - P_0}{a}. \quad (2)$$

The zero temperature coefficient

$$\alpha_0 = \frac{a}{P_0} \quad (3)$$

(that is, the change in pressure per degree divided by the pressure at 0°) is also a constant, and has the value 0.0036, or about $\frac{1}{273.4}$ for all gases. The true pressure coefficient α , or the relative change in pressure per degree, is not a constant for an ideal gas but must decrease at higher temperatures, since P being in the denominator increases.

In the operation of the instrument, shown in Fig. 2, certain errors are always introduced and must be accounted for. As the temperature of the bulb is raised, the actual volume of the bulb increases for two reasons: first, due to the thermal expansion of the bulb; and, second, due to the fact that at the higher temperature, the increased pressure within causes an elastic expansion, *i.e.*, the volume of the bulb and, hence, also that of the contained gas is greater at the higher temperature. The effect due to the thermal expansion of the material of the bulb in the case of glass amounts to a correction of about 0.75 per cent. It is about the same for platinum. The correction due to the pressure expansion is difficult to compute and in precise work is overcome by using a bomb-type heating device in which the same pressure may be maintained as that within the bulb.

An additional correction arises from the fact that the capillary tube which connects the gas bulb to the manometer has its temperature changed only slightly as the temperature of the bulb is raised to its highest value. Hence, some of the air which resided in the bulb at the lower temperature will be crowded into this so-called "dead" space at the higher temperature. Care should be taken to observe the temperature of the mercury in the manometer so that pressures are always expressed in terms of mercury under standard conditions. The effect of some of these corrections may be shown by writing an equation in which the total amount of gas

in the bulb and dead space at the lower temperature is set equal to the combined mass at the higher temperature. If there is no change in pressure, the density of a gas at any temperature t° is related to the density at 0° , as follows:

$$\rho_t = \frac{\rho_0}{1 + \alpha t}$$

Hence, it follows that

$$V_0 \rho_0 + v \frac{\rho_0}{1 + \alpha t_1} = V_0 \frac{1 + gT}{1 + \alpha T} \frac{P}{P_0} + v \frac{\rho_0}{1 + \alpha t_2} \frac{P}{P_0} \quad (4)$$

where the letters have the following significance:

V_0 = volume of bulb at zero.

ρ_0 = density of gas at zero.

v = volume of dead space.

t_1 = temperature of dead space at start.

α = temperature coefficient of the gas (really volume).

g = temperature coefficient of the container (volume).

P_0, P = pressure at 0° and T° , respectively.

T, t_2 = final temperatures of bulb and dead space, respectively.

The equation may be solved for T or for α depending upon whether or not the operation is a calibration using fixed temperatures or the measurement of an unknown temperature. Neglecting those terms involving the product of expansion coefficients, the temperature T may be expressed as

$$T = \frac{(P - P_0)1 + \alpha(t_1 - t_2) + v/V_0[1 + \alpha(t_1 - t_2)]}{P_0\alpha - Pg - \alpha(P - P_0)v/V_0} \quad (5)$$

Should $g, t_1 - t_2$, and v/V_0 be negligible, this equation reduces to Eq. (2) above.

Since the value of α_0 as defined above is numerically about $1/273$, it must follow that at a temperature of -273°C . the pressure is 0. Should a constant-pressure gas thermometer be used, and the changes in volume be taken as an indication of the temperatures then also for those gases which obey Boyles law, measurements from 0 to 100° indicate that at -273°C . the volume of the gas would become zero. This temperature is therefore called the absolute zero and

Centigrade-thermometer readings may be expressed in the absolute scale by adding to each reading the value 273.4.

From elementary kinetic theory the pressure of a gas is related to the effective velocity of the gas particles as follows:

$$P = \frac{1}{3} \rho v^2,$$

where ρ is the density of the gas and v^2 the average square velocity of the particles. If the pressure is zero, it would then follow that the particles were at rest since ρ must be constant in the normal thermometer. The notion of zero volume, which would follow from the constant-pressure gas thermometer at the absolute zero, is untenable. It would be better to say that at that temperature the volume is the minimum volume of the gas particles at rest; such a volume as enters as a correction term in the Van der Waal equation of state.

That temperatures measured by a constant-volume gas thermometer should agree with those of the normal thermometer provided the gas obeys Boyle's law may be shown to follow, by allowing the temperature of a certain amount of gas to change from t_0 to t , first under the condition of constant pressure and secondly under the condition of constant volume. By taking t_0 as 0°C. and writing expressions for the product PV at the temperature t , it follows that

$$(PV)_t = P_0 V_t = P_0 V_0 (1 + \alpha_v t) = P_t V_0 = P_0 V_0 (1 + \alpha_p t) = P_0 V_0 \left(1 + \frac{t}{273}\right) = \frac{P_0 V_0}{273} T = RT. \quad (6)$$

Most gases obey Boyle's law very closely at temperatures distant from their condensation points. When used for temperatures close to the condensation point, the error in the normal thermometer is surprisingly small. Kammerlingh Onnes¹ tested this effect by comparing a hydrogen thermometer with a helium thermometer at temperatures close to the condensation point of

¹ *Proc. Acad. Amsterdam*, vol. 10, p. 743.

hydrogen and found that the error was negligible when distant from the condensation point by 0.5°C .

The Thermodynamic Temperature Scale.—Carnot, in 1824, showed that any reversible thermodynamic engine, which took in some quantity of heat H_1 at a temperature T_1 and, after doing a certain amount of work W , gave to a condenser at some lower temperature T_2 a quantity of heat H_2 , should have an efficiency as follows:

$$\text{Efficiency} = \frac{H_1 - H_2}{H_1}.$$

It further follows from the second law of thermodynamics that the efficiencies of all reversible engines working between these two temperatures must be the same regardless of the nature of the working substance. Lord Kelvin suggested that this might serve as the basis of a temperature scale and this scale would have the advantage that it would not be dependent upon any particular property of matter. If the quantities of heat absorbed or ejected at any temperature be taken as proportional to that temperature, then the expression for efficiency may be written:

$$\text{Efficiency} = \frac{KT_1 - KT_2}{KT_1} = \frac{T_1 - T_2}{T_1}.$$

On this scale then any two temperatures have the ratio of the quantities of heat absorbed and ejected by a cyclic reversible engine working between these temperatures. The numerical values of temperatures may be assigned by agreeing upon the values of two fixed points as in any of the other temperature scales.

Now it happens that if an actual gas be considered as taken about a Carnot cycle and the expression for the efficiency obtained by considering the gas ideal, the following expression is obtained:

$$\text{Efficiency} = \frac{T_1 \log_e V_2/V_1 - T_2 \log_e V_2/V_1}{T_1 \log_e V_2/V_1} = \frac{T_1 - T_2}{T_1}$$

where T_1 and T_2 are measured on the gas scale.

The ideal gas must obey both the Gay-Lussac law and the law of Joule (*i.e.*, its internal energy must be a single valued function of the temperature only). Thus, the gas thermometer, which is very exact for most of the permanent gases, indicates temperatures on the thermodynamic scale to the degree that the gas obeys the above laws. The corrections to be applied to the temperatures observed on the gas thermometer to reduce them to thermodynamic temperatures may be calculated from a knowledge of the divergence of the gas from the above-mentioned laws. Callendar¹ has computed the following deviations for hydrogen and nitrogen at the temperatures mentioned, assuming the scales to agree at 0°C.:

TABLE I

Thermodynamic temperatures in degrees Centigrade	Correction	
	Hydrogen	Nitrogen
-100°C.	+0.005	0.08
0	0	0
200	0.0024	0.035
450	0.013	0.189
1,000	0.044	0.646

Limitations of the Gas Thermometer.—At low temperatures, the gas thermometer is usable close to the condensation point of the gas employed. For very low temperatures then helium has an advantage. Owing to the awkwardness of the large bulb, however, Kammerlingh Onnes² has generally found it preferable to use the gas thermometer only to calibrate noble-metal thermocouples for use in this temperature range. At high temperatures the bulb must be made of a material whose expansion coefficient is accurately known and at the same time the bulb must neither emit gases nor allow them to diffuse either into or out of the bulb.

¹ *Phil. Mag.*, vol. 48, p. 519, 1899.

² *Loc. cit.*

Using bulbs made of platinum and iridium alloys, and nitrogen as the working gas, Day and Sosman¹ were able to make accurate determinations of certain fixed points up to the melting point of palladium, $1553 \pm 3^\circ\text{C}$. Great care had to be exercised in this research to insure valid results. Since the gas thermometer is so difficult to work with, it is more convenient to calibrate other secondary devices in terms of the gas thermometer and use them in the actual temperature measurement.

The fact that the gas scale is fundamental by agreement, should not be overlooked, however, and since it has not been used above 1550°C ., higher temperatures can only be measured by extrapolating certain laws which have been found to hold true below this value. Hence, for these higher temperatures, an element of uncertainty exists and it is only by extrapolating with several different laws, which have been independently verified in the known region, and by obtaining in each case the same value at the higher temperature that confidence is placed in the result. The uncertainty attendant upon extrapolations of this sort is well illustrated by the following early experiment in high-temperature measurement carried out by Wedgewood.² He attempted to measure temperature by the shrinkage caused by that temperature upon a certain sample of clay. The measuring of the shrinkage for the known temperature interval from the freezing to the boiling point of water sufficed for a calibration of the instrument. By comparing this shrinkage with that which took place when the clay was placed in a furnace at the temperature of melting iron, he expressed the melting point of iron as about 12000°C ., a value about 10500° too large.

Fusion Pyrometers.—It is possible to obtain a series of materials with progressive melting points differing from each other by certain known amounts. By molding these materials in the form of cylinders or cones and arranging them in order on a tray, it becomes possible to estimate temperatures by observing the collapse of the

¹ See Ref. on page 4.

² *Phil. Trans.*, vol. 72, p. 305, 1782; vol. 74, p. 358, 1784.

figures. Metals, salts, or clays are suitable for this work. Seger,¹ in 1886, developed a series of materials by using mixtures of Al_2O_3 , SiO_2 and SiO_3 , B_2O_3 in varied proportions, such that they possessed melting points from 1800 to 590°C. with small steps between successive members. These samples are made in the form of small pyramids and are called Seger cones. These appliances are satisfactory where it is desirable simply to heat a furnace to some definite temperature and then allow it to cool. The cones are very cheap and only those whose melting points lie in the neighborhood of the final temperature need be used.

EXPERIMENT

GAS THERMOMETER

OBJECT: Temperature measurement and pressure coefficient of air.

Place a 0 to 100°C. thermometer close to the bulb of a gas thermometer and read when reading the following pressures:

Find the pressure of the gas when the bulb is surrounded by melting ice.

Repeat at the boiling point of water.

Compute the boiling temperature of water for the existing barometric pressure.

Immerse the bulb of both thermometers in a thermos bottle filled with water warmed to about 40°C. Read the mercury thermometer and, making any corrections necessary for errors at 0 or 100°C., express the temperature. Read the pressure of the gas thermometer and by means of the previous readings calculate the gas temperature. Should the two readings agree? Discuss.

From the first two readings calculate the zero temperature coefficient of pressure of the gas. Repeat the calculation where the volume of the dead space and expansion of glass is considered. Discuss errors such as the presence of water vapor in the gas.

The total mass of gas in the bulb and dead space at the low and high temperatures must be the same. If V_0 denotes the volume of the bulb at 0°C., P_0 the pressure of the gas at 0°C., v and t the volume and temperature of the dead space, d_0 the density of air at zero degrees, α coefficient of pressure of the gas under constant volume, and g coefficient of cubical expansion of glass, the two expressions for the total mass of gas at 0°C. and $T^\circ\text{C.}$, follow:

$$V_0 d_0 + \frac{v d_0}{1 + \alpha t} = \frac{V_0 (1 + gT) d_0}{1 + \alpha T} \cdot \frac{P}{P_0} + \frac{v}{1 + \alpha t} \cdot \frac{P}{P_0}$$

¹ *Tonind.-Zeit.*, p. 121, 1885; pp. 135, 229, 1886.

Simplifying and neglecting terms containing α^2 and αg and solving gives

$$\alpha_0 = \frac{\Delta P + gTP + \Delta P \frac{v}{V_0}}{P_0 T - \Delta P \frac{v}{V_0} t},$$

which reduces to $\frac{\Delta P}{P_0 T}$ when g and v are negligible.

CHAPTER III

THERMOELECTRIC PYROMETERS

A simple thermoelectric pyrometer consists of a thermocouple, an indicator or recorder of some type, and suitable lead wires connecting the two. A thermocouple is made by welding two dissimilar metal wires together at one end. If the opposite ends are connected to the two poles of an instrument indicating e.m.f., and the junction heated, an e.m.f. will be generated in the wires, the value of which may be read on the instrument. If the cold ends of the thermocouple are maintained at a constant and known temperature, and the wires are of suitable composition, there will be a uniform increase of e.m.f. as the temperature of the hot end of the couple is increased. It is then possible to calibrate this system and make of it a temperature-measuring device.

THERMOCOUPLES

Thermoelectric Currents.—The existence of these so-called thermoelectric currents was discovered by Seebeck¹ in 1821, while experimenting on the difference of potential which was thought to exist when two metals were placed in contact. It was noted, for instance, that if the ends of a copper and an iron wire were fused together and one of the junctions heated (over a particular temperature range), an e.m.f. was generated, and current flowed from the copper to the iron wire at the hot end and from the iron to copper at the cold end. Two sources of e.m.f. combine to cause the flow of this current. One of these sources is known as the Peltier e.m.f. and the other as the Thomson e.m.f.

¹ "Fundamental Principles," *Pogg. Ann.*, vol. 6, pp. 133, 263, 1826.

The Peltier E.m.f.—Peltier discovered in 1834 that when an electric current is passed through the junction of two metals there will be either an evolution or an absorption of heat at the junction, depending upon the direction in which the current is made to flow. This indicates that there is a difference of potential at the junction of the two metals, and when the current is made to flow against this e.m.f. excess heating is produced, while if made to flow in the direction that the e.m.f. would produce a current, a cooling effect appears. It may be noted that this potential difference varies with the temperature of the junction. This is a continuous and direct variation in some cases, while in others the e.m.f. may rise to a maximum and then decrease with increase of temperature. It is desirable that this variation be uniform in order that the system may be used for measuring temperature. The number of metals or alloys in which this condition is met is somewhat limited. This so-called Peltier e.m.f. is responsible for a portion of the e.m.f. observed in all thermocouples.

The Thomson E.m.f.—While studying phenomena attendant upon the production of the Peltier effect, Lord Kelvin¹ was led to conclude that in a closed circuit made up of dissimilar wires there are other sources of e.m.f. than are accounted for by the Peltier effect. His further work finally brought out the fact that a difference of potential exists in a single section of wire when there is a temperature gradient between the ends. For instance, if a section of copper wire is heated at one end, there will be an e.m.f. set up from the hot to the cold end. As in the case of the Peltier e.m.f., the intensity and direction of the Thomson e.m.f. vary in different metals. The presence of this e.m.f. was demonstrated by observing the temperature variations on both sides of a heated point in a wire when an electric current was made to flow first in one direction and then in the other. It was observed that the temperature rose on one side and fell on the other when the current was passed in one direc-

¹ *Trans. Roy. Soc. Edinburgh*, vol. 21, p. 123, 1854; *Phil. Mag.* (4), vol. 11, pp. 214, 281, 379, 433, 1856; *Compt. rend.*, vol. 39, p. 116, 1854.

tion. On reversing the current, the side which was heated previously was cooled, while the other side was warmed. This may be demonstrated by an apparatus such as that shown in Fig. 4. The shaded portion *A* of a metal rod *MN* is heated and an electric current caused to pass in the direction of the arrow. *b* and *c* are two points at such distance from *A* that their temperatures are equal before the current is made to flow. After the current is flowing, the temperature at one point will rise, while the other will drop. Reverse the current and the opposite effect will be noted.

Nature of Electrothermal Effects.—At the present time no theoretical explanation of these electrothermal effects is completely in accord with all experimental data. By considering the complete thermocouple attached to a dynamo-electric machine with a neg-



FIG. 4.—Demonstration of the Thomson e.m.f.

ligible ohmic resistance in the circuit, the arrangement may be considered as a reversible heat engine. If one junction is heated above the other, heat will be absorbed at the hot junction and a certain part of this used to do work in the dynamo-electric machine now functioning as a motor, and a certain amount of heat will be ejected at the cold junction similar to the condenser or low-temperature reservoir of a heat engine. Now if this process be considered as obeying the first law of thermodynamics, one equation is obtained involving for the complete process a Peltier coefficient *P*, and a Thomson coefficient σ . These coefficients are defined as follows: *P* represents the number of heat units evolved or absorbed at the junction when unit quantity of electricity flows across the junction; σ represents the heat evolved within a metal when unit quantity of electricity flows from one region to a neighboring region differing in temperature by 1° .

$$Eq = P_1q - P_2q + q \int_{T_1}^{T_2} \sigma_a dT - q \int_{T_1}^{T_2} \sigma_b dT. \quad (1)$$

The second law of thermodynamics for any cycle when considered reversible is

$$\int \frac{dW}{T} = 0,$$

or in this case,

$$\frac{P_1}{T} - \frac{P_2}{T} + \int \frac{\sigma_a dT}{T} - \int \frac{\sigma_b dT}{T} = 0. \quad (2)$$

The solution of these two thermodynamic equations gives

$$P = T \frac{\partial E}{\partial T} \quad (3)$$

and

$$\sigma_a - \sigma_b = T \frac{\partial^2 E}{\partial T^2}. \quad (4)$$

Hence, for any thermocouple whose e.m.f.-temperature relation is given by a second-degree equation such as $E = a + bT + cT^2$, the Eq. (4) for the difference in Thomson coefficients for the two metals would appear to be given by $2cT$; while the Peltier coefficient P from Eq. (3) would equal $bT + 2cT^2$. Now should c be negative and b positive, there would be some value of T beyond which the Peltier effect would reverse.

For a couple whose calibration curve for e.m.f.-temperature is a straight line, such as most of the base-metal couples in use ($E = a + bT$), the Peltier coefficient P would equal bT , and the total Thomson effect $\sigma_a - \sigma_b = 0$ at all temperatures. Experiment seems to indicate that the Thomson effect for a pure metal may actually reverse at certain temperatures.

These phenomena should be explainable by the free electron theory, which has met with considerable success in the field of thermal and electric conductivities. As the temperature of the metal is increased, the number of free electrons per unit volume might be expected to increase directly. The average kinetic energy of the electrons should also increase but the mean free path of the electrons would decrease. The combination of these effects will influence the flow of electrons from one region to another within a given metal or across the contact surface by which it is connected to another metal. The first two effects would aid, while the last-

named effect would hinder, electron diffusion. Since these combined effects might vary for different metals in different degrees with temperature, a reversal of the Peltier coefficient would be possible. A reversal of the Thomson effect might also be possible if the combined effect for a given metal varies irregularly with temperature. A substance negative with respect to most other metals, such as constantan, would therefore have a tendency to lose electrons across the surface of contact with these other metals. Such a flow of electrons would reduce the temperature, unless heat were absorbed to compensate for the loss. When the current is made to flow in the reverse direction, electrons would be forced into regions from which others wished to depart, resulting in an increased temperature unless connected to a constant-temperature source.

Lead appears to have a zero Thomson effect and is therefore generally taken as a reference metal in thermoelectric power tables, although any other metal, such as platinum, could be used.

Preparation and Operation of Thermocouples.—In order to prepare a thermocouple which will generate a usefully large e.m.f., it is necessary to choose wires whose Thomson e.m.fs. are opposite in phase and exhibit direct variation with temperature. In addition, the Peltier e.m.f. at the hot junction of the couple must be such that the wire showing the negative Thomson e.m.f. will be the positive element as far as the Peltier e.m.f. is concerned. The Peltier e.m.f. must also vary directly with temperature. Under these circumstances the e.m.fs. will all be additive and their sum will vary directly with the temperature, provided the cold junctions of the wires are held at a constant temperature. This will produce the maximum current as registered on the indicator. Such a system is illustrated in Fig. 5. *M* is the hot junction of the couple, *N* the cold junctions, *a* the positive wire, *b* the negative wire, *G* the galvanometer, and *x* and *y* the lead wires.

While cold-junction errors will be discussed more fully later, it will be well to point out at this time just why it is necessary that

the cold junctions N in Fig. 5 must be kept at a constant temperature. The leads x and y are usually copper wires. At the points N , these copper wires are in contact with wires a and b of the couple, the connection being completed through the galvanometer. Such a situation means that there is a small counter-Peltier effect between points N . If these points are allowed to fluctuate in temperature, this Peltier effect will vary, and will cause errors in the e.m.f. which is being produced due to the temperature of the hot end of the couple.

Further, if the temperature of the cold junction rises, the hot end remaining constant, the Thomson e.m.f. in wires a and b will

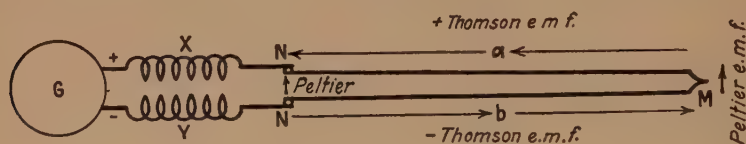


FIG. 5.—Sources of e.m.f. in a thermocouple.

be reduced, producing a further error. Let it be emphatically stated, then, that the temperature of the cold junctions *must* remain constant, unless suitable compensation for the error is provided.

Another question grows out of this consideration. What will be the effect of heating one or both wires of a thermocouple at some point between the hot and cold junctions? Consider, for instance, that the hot end of a certain couple is at $700^{\circ}\text{C}.$, the cold junctions at $0^{\circ}\text{C}.$, and the wires heated to $1000^{\circ}\text{C}.$ at some point between the two junctions. Unless there is inhomogeneity of the metal or conduction of heat along the wires to one or both the junctions, the e.m.f. generated will be that produced by the hot junction as if there were no intermediate heating of the wires. The reason for this is easily explained. When the wires are heated to $1000^{\circ}\text{C}.$ at an intermediate point, the Thomson e.m.f. only will be affected. From the point at $1000^{\circ}\text{C}.$ to the hot end of the couple, there will be a Thomson e.m.f. generated due to the $300^{\circ}\text{C}.$ differ-

ence between the two points. Between the point at $1000^{\circ}\text{C}.$ and the cold ends at $0^{\circ}\text{C}.$, an *opposite* Thomson e.m.f. will be generated due to the $1000^{\circ}\text{C}.$ difference between the two. The resultant e.m.f. will be the algebraic sum of the two e.m.f.s. generated in the wires, which, of course, will be the e.m.f. generated by a temperature of $700^{\circ}\text{C}.$ at the hot end of the couple. In other words, the e.m.f. generated by a thermocouple, except in situations where there is inhomogeneity or noticeable heat conduction along the wires, is due *only* to the difference in temperature between the hot and the cold junctions of the couple, and the temperature indicated is only that at the hot junction.

Thermoelectric Power of Thermocouples.—The e.m.f. produced by thermocouples is always very small. There is, of course,

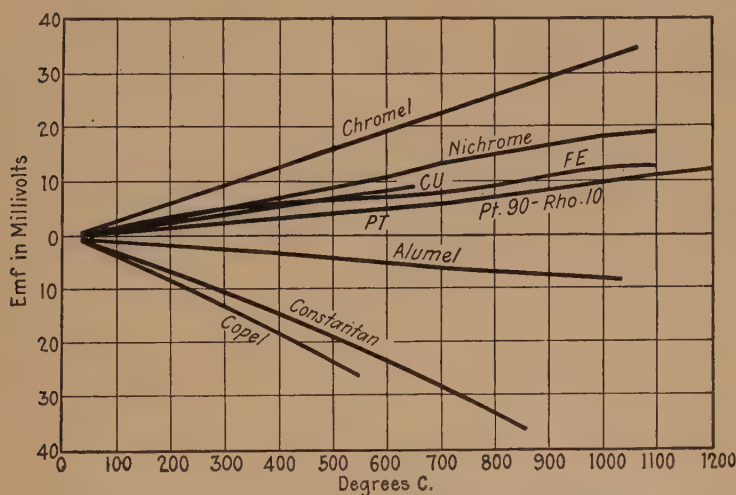


FIG. 6.—E.m.f.-temperature relation of metals and alloys commonly used in making thermocouples.

considerable variation in the different types of couples, the maximum range for metals commonly used being about 0 to 0.075 volts. Figure 6¹ represents the e.m.f.-temperature relation of metals and alloys commonly used in making thermocouples, *versus* platinum, the cold junctions being at $0^{\circ}\text{C}.$ It will be noted that the

¹ Partial reproduction of Fig. 165, *U. S. Bur. Standard Tech. Paper 170*.

upper curves represent materials which are positive and the lower curves those which are negative to platinum. The e.m.f. of a combination of any two of these materials at a given temperature may be ascertained by measuring in millivolts the vertical distance between the two curves. In all cases the upper curve indicates the positive element of the couple.

The e.m.f. per 1° rise in temperature is sometimes referred to as the thermoelectric power of a couple, and furnishes a convenient means of comparing the same or different types of couples over various ranges. It is obtained by determining the first derivative with respect to temperature of the expression $E = f(t)$, where E is e.m.f. and t is temperature. The same information may, of course, be found approximately from inspection of curves such as are found in Fig. 6.

Required Properties for Thermocouples.—While some reference has been made in the discussion so far to the thermoelectric requirements of thermocouples, other properties should be considered. Little beyond a brief enumeration of desirable properties will be made at this point, it being more convenient to cover them in detail in the discussions dealing with particular types of thermocouples.

1. *Direct Variation of Temperature and E.m.f.*—This has been fully discussed previously.

2. *Resistance to Corrosion and Oxidation.*—It is quite obvious that the elements of the thermocouples must have a reasonable amount of resistance to these actions. A bare iron wire, for instance, will deteriorate too rapidly.

3. *Development of Relatively Large E.m.fs.*—The accurate determination of the e.m.f. of a couple which has an extremely low thermoelectric power requires a delicate instrument. Great care should be taken. It is quite obvious, therefore, that a couple possessing a larger thermoelectric power will have a greater utility.

4. *Constancy of Calibration.*—Changes in the calibration of thermocouples may result from various causes. It need hardly

be stated that no couples should be made from metals or alloys which deteriorate rapidly upon exposure to temperatures in the range over which they are expected to operate. Contamination by furnace fumes and oxidation will cause inhomogeneity of couples and consequent variations in e.m.f.-temperature relationships.

5. *Reproducibility of Couples*.—In laboratory work this point is not of great importance. In plant work, however, where a large number of couples are being used, and where several couples may be read on one instrument which is graduated in degrees of temperature only, it is very essential that there be no marked variation in couples of the same type. In any case in which a great variation exists, it necessitates the application of a correction, and that is almost out of the question in an installation of any size.

Noble-metal Thermocouples.—Becquerel¹ in 1826 first applied the discovery of Seebeck to the measurement of high temperatures. He used a platinum-palladium couple but obtained no satisfactory results. Considerable work was done by other investigators, but the thermoelectric pyrometer was not successfully used until after the investigations of Le Chatelier.² He finally perfected and introduced the couple whose positive element consists of 90 per cent platinum and 10 per cent rhodium, the negative element being a pure platinum wire. Barus³ at about the same time recommended the use of a couple whose positive element consists of 90 per cent platinum and 10 per cent iridium, and whose negative element is pure platinum. This latter couple develops a greater e.m.f. than the couple of Le Chatelier, but there is a gradual distillation of the iridium from the alloy wire, especially at high

¹ *Ann. chim. phys.* (2), vol. 31, p. 371, 1827.

² "Thermoelectric Pyrometer," *Compt. rend.*, vol. 102, p. 819, 1886; also, *Jour. phys.* (2), vol. 6, January, 1887.

³ *U. S. Geol. Survey Bull.* 54 and 103. *Phil. Mag.* (5), vol. 34, pp. 15, 376, 1892. *Am. Jour. Sci.*, vol. 36, p. 427, 1888; vol. 47, p. 366, 1893; vol. 48, p. 336, 1894.

temperatures. This causes the e.m.f. to drop gradually and necessitates frequent recalibration of the couple.

From what has just been said, it is evident that the first types of thermocouples to come into general use were made of the noble metals. After the successful application of these couples, a considerable period elapsed during which no other type of couple was introduced, although the fact was appreciated that the cost of couples made of platinum was almost prohibitive in many cases. The last twenty years have seen the development and successful application of the cheaper base-metal couples. The range of base-metal couples is in all cases less than that of noble-metal couples, and as their determinations are less accurate, many applications yet remain for the noble-metal couples. Laboratory work requiring high precision, the hardening of high-speed steel, maintenance of standards for base-metal couples, and control of high-temperature kilns are included among these.

Preparation.—Noble-metal couples may be purchased already mounted, or if desired, the wire may be bought from the platinum refiners and made into couples in the laboratory. Figure 7 illustrates a noble-metal couple with its primary mounting, the two wires being threaded through two-holed porcelain cylinders. Each wire terminates at a binding post on the head of the mounting. Figure 8 shows this same couple encased in a primary protecting tube. Such a mounting is used in high-speed steel furnaces. Figure 9 shows the above couple installed in a glass melting tank. The cold junction may be at the head of the couple or by the use of suitable leads may be removed to any convenient distance. Provision is made in this installation for the insertion of a test couple.

If the couples are made in the laboratory, it is necessary to fuse the ends of the two elements together. This may be done by means of an electric arc or a small oxygen-illuminating gas flame. Acetylene should not be used since the wires become embrittled due to the formation of platinum carbide. The welding flame is

conveniently produced by a small torch. The flame of the torch should be about 4 centimeters long. The torch is supported by suitable means and the two ends of the wires held in the flame until they fuse together in a small bead. No flux should be used.

Calibration.—Before calibration a noble-metal couple should be annealed electrically for a period varying from 30 minutes to 2 hours, at about 1500°C . The purpose of the annealing is to produce homogeneity in the wire. In case there are hard and soft

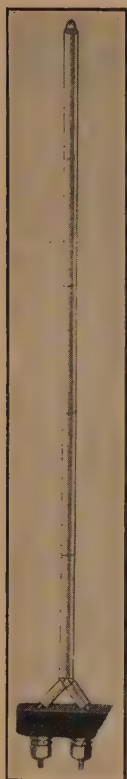


FIG. 7.

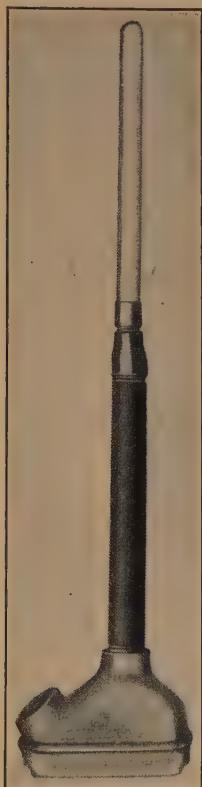


FIG. 8.

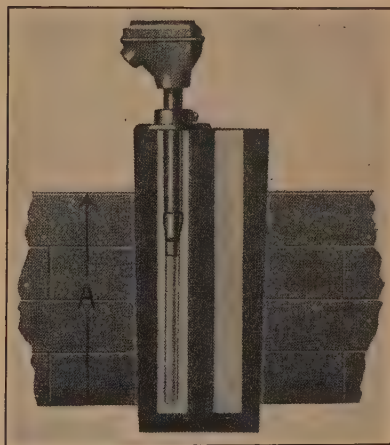


FIG. 9.

FIG. 7.—Noble-metal thermocouple with its primary mounting. (*Republic Flow Meters Co.*)

FIG. 8.—Noble-metal thermocouple mounted in primary protecting tube. (*Republic Flow Meters Co.*)

FIG. 9.—Noble-metal thermocouple installed in a glass melting tank. (*Republic Flow Meters Co.*)

spots parasitic e.m.fs. are set up which introduce errors. The annealing operation is carried out by suspending the couple between two binding posts in a 110-volt circuit. The current required depends upon the size of the wire, varying from about 10 to 14 amperes as the diameter of the wire varies from 0.4 to 0.6 milli-

meters. In the case of old and badly contaminated couples, the time of annealing may have to be increased to as much as 2 hours.

If there is any doubt as to the homogeneity of a noble-metal couple, and precise work is required, a homogeneity test should be applied. Uncontaminated reference specimens of each type of wire are required for this. One end of the standard wire is placed in contact with the corresponding wire of the couple to be tested. This junction is then heated, and any e.m.f. between the cold ends of the couple wire and the reference wire is recorded. This procedure is carried out at several points along the couple wire. If the couple wire is homogeneous no e.m.f. will be generated. In a similar manner the other element of the couple is explored. For detailed description of this test, see *Technologic Paper* 170; of the U. S. Bureau of Standards, page 228.

An inhomogeneous couple indicates the temperature of the hot junction only when the region of inhomogeneity lies completely on one side or the other of the region of temperature gradient on the couple.

The temperature-e.m.f. relation of the platinum, platinum-rhodium thermocouple in the range 300 to 1200°C. is expressed by the equation

$$E = a + bt + ct^2$$

where E = e.m.f., t = temperature in degrees Centigrade of the hot junction of the couple, (cold junction at 0°C.) and a , b , and c are constants. The constants are different for each couple and require three standard points for their determination. These points are usually the melting or freezing points of three metals (see Experiment 4). The e.m.fs. of the couple at these three points are obtained and inserted in the first member of the equation. Three equations are thus obtained which are solved simultaneously for a , b , and c . The following is a typical expression for a couple of this type;

$$E = -0.323 + 0.008276t + 0.000001638t^2.$$

Using this equation, a calibration curve of temperature *versus* e.m.f. may be prepared. Above 1200°C. the following corrections must be added to the temperatures given by the equation.

TABLE II

TEMPERATURE COMPUTED FROM PARABOLIC EQUATION, DEGREES CENTIGRADE	CORRECTION TO ADD, DEGREES CENTIGRADE
1200	0
1300	2
1400	6
1500	14
1600	25
1700	39

For temperatures below 300°C. the above equation does not apply, and it is usually expedient to employ some other type of pyrometer. In this range the noble-metal couples are rarely used.

The calibration which has just been described is termed the primary calibration and may be made by a standardizing laboratory. In the secondary calibration the actual couples to be used are compared with a standard couple which has been previously calibrated.

Base-metal Thermocouples.—In installations requiring large numbers of thermocouples the cost of using platinum, platinum-rhodium couples would be very high. For this reason, if for no other, there has been an insistent demand for couples which will give reasonable service and be made from the less-expensive metals. Almost numberless combinations of metals and alloys have been investigated but until the present time comparatively few successful base-metal couples have been developed. No space will be given here to the fundamental investigations in connection with this type of couple. This work has been carried out to a great extent in industrial laboratories and much of the material has not been published. In the present discussion the more important types of base-metal couples will be listed and their characteristics and applications discussed.

Much of the effort along this line has been made with a view of producing as nearly as possible what is termed a "straight-line"

couple. In such a couple the temperature is a linear function of the e.m.f. and the relationship when plotted is a straight line. The advantages of such a couple are very evident. In the first place, the calibration curve requires the establishment of only two standard points. Another important advantage lies in the fact

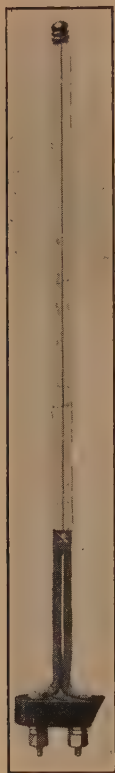


FIG. 10.—Base-metal couple with its primary mounting. (*Republic Flow Meters Co.*)

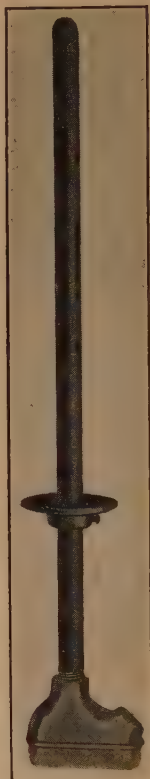


FIG. 11.—Base-metal couple with wrought iron protecting tube. (*Republic Flow Meters Co.*)

that in checking couples of this type it is necessary to check only one point. In other words, the per cent error is nearly constant. Much time in checking large installations is thereby saved. Perhaps the most useful feature of straight-line couples is in the application of cold-junction corrections. In most cases, this involves merely the addition or the subtraction of the difference between the

actual temperature of the cold junction and the temperature at which the original calibration was carried out. For instance, suppose a couple originally calibrated at a cold-junction temperature of 0°C . is being used with a cold-junction temperature of 15°C . In order to obtain the correct temperature at the hot junction, it is only necessary to add 15°C . to the indicated temperature. If the cold junction were at -15°C ., the 15° difference would be subtracted from the indicated temperature.

Base-metal couples are made in sizes ranging from 0.02 up to 0.25 inch in diameter. The couples may be bought completely mounted or the wire may be purchased and couples made by the user. Figure 10 illustrates an ordinary base-metal couple with its primary mounting. For many laboratory operations, this is all the mounting that is necessary. Figure 11 represents a base-metal couple completely mounted in a wrought-iron protection tube for use up to 1400°F . If higher temperatures are required, different types of protecting tubes must be used.

A study of Fig. 6 will reveal the various types of base-metal elements which are used in the production of thermocouples. The following combinations are the ones usually found in practice:

1. Chromel (+)..... Alumel (-)
2. Iron (+)..... Constantan (-)
3. Copper (+)..... Constantan (-)
4. Chromel-X (+)..... Copel (-)

While this list perhaps does not cover all the couples on the market today, it will almost invariably be found that couples which are not admittedly of one of the above types are in fact only modifications.

The *chromel-alumel* couple is used very widely at the present time. The chromel, or positive, element is an alloy consisting of about 90 per cent nickel and 10 per cent chromium. The alumel, or negative element, carries about 94 per cent nickel, 2 per cent aluminum, 3 per cent manganese, and 1 per cent silicon. This

couple may be used intermittantly for temperatures up to 2400°F. (1315°C.) and continuously for temperatures up to 2000°F. (1094°C.). It's calibration curve is very nearly a straight line, so that cold-junction errors may be corrected by mere additions or subtractions of the differences between actual cold-junction temperature and the cold-junction temperature of the calibration curve. They are very durable and will give good service for several months with very little attention. It is possible to purchase coils of chromel and alumel wire from which couples can be made as needed, without calibrating each couple. Before making any couples, however, for precision work, sections from such coils should be checked against a standard such as platinum in order to be sure that the millivoltage values of the alloy wire are correct and that there are no wide variations in different sections of the coil. The procedure indicated above should be followed in the case of any alloy wire which is to be used as a thermocouple element. The e.m.f. per degree Centigrade is about 0.04 millivolt.

The *iron-constantan* couple is also one which is used to a great extent. The positive element consists of carefully made pure-iron wire and the negative element of the 60 per cent copper and 40 per cent nickel alloy known as constantan.

This couple may be safely used up to a temperature of 1800°F. (982°C.) providing proper precautions are made to prevent oxidation and contamination of the wires. Two methods are used to accomplish this. One is to pack the secondary protecting tube of the couple with a material which is slightly reducing in nature, such as a 97 per cent alumina and 3 per cent charcoal mixture. Figure 12 represents the other method of construction. An iron tube is made the positive element of the couple and the constantan wire or rod placed inside the tube, the two being fused together at one end. Asbestos cord is used to insulate the two elements. The iron tube furnishes protection to the constantan element and is not so quickly deteriorated by oxidation. For severe

furnace conditions, however, even this sort of couple must be protected by an outer tube. The thermoelectric power of this couple is about 0.055 millivolt.

The *copper-constantan* couple is useful for temperatures up to 1000°F. (537°C.). Its greatest utility is in the lower ranges, for its calibration curve remains nearly straight at temperatures in the neighborhood of the boiling point of water, and its thermoelectric power is high enough so that accurate readings of temperature may be made in that range. It is generally possible to dispense with the protecting tube when this couple is being used for low-temperature work.

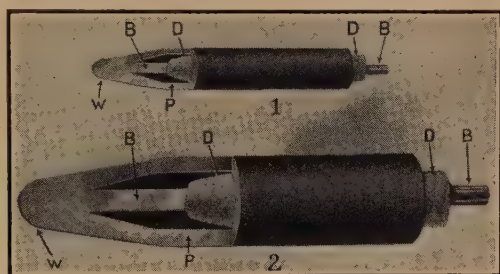


FIG. 12.—Thermocouple having one element in the shape of a tube surrounding the other element. (Wilson-Maculen Co.)

An interesting application of the copper-constantan couple is in the measurement of temperatures below zero. Adams¹ states that it is probably possible to make temperature measurements as low as -253°C . with this couple. Values of the temperature-e.m.f. relationship for low temperatures have been determined by the above investigator. When using a couple in this range, it should be kept in mind that there is a reversal of the direction of the e.m.f. as the temperature passes downward through zero, the cold junction remaining at zero.

The *chromel-X*, *copel* couple is also suitable for the range of temperature below 1000°F. on account of its correspondingly higher

¹ ADAMS, L. H., "Pyrometry," Symposium, *Am. Inst. Mining Met. Eng.*, p. 165. 1920.

e.m.f. Chromel-X is an alloy carrying about 64 per cent nickel, 25 per cent iron, and 11 per cent chromium. Copel contains 45 per cent nickel and 55 per cent copper.

The chromel alloys, alamel and copel are made by the Hoskins Manufacturing Company of Detroit. Constantan may be bought on the open market under trade names such as "Advance" and "Ideal."

Base-metal couple junctions are made by fusing the ends of the two elements together by means of an electric arc or an oxygen-illuminating gas torch. In the case of the larger wire sizes, it is advisable to twist the two wires for a few turns before welding. This gives added mechanical strength to the couple and brings the two ends to be fused conveniently close together. If an electric arc is used, the two couple wires are fastened to the positive terminal of a 110-volt, direct-current line. The negative terminal is connected through a resistance to a graphite pencil about $\frac{1}{4}$ inch in diameter, having an insulated handle. Having brought the ends of the wires together, the junctions are touched with the graphite pencil. As soon as an arc is formed, the pencil is drawn away. This method is very good for the repairing of broken couples. If the junction is to be made by means of an oxy-gas flame, it should be first coated thoroughly with borax. This is accomplished by heating the ends of the wires to a dull red heat and then dipping them into a dish of powdered borax. The process should be repeated until there is a heavy coating of transparent borax around the junction. The full heat of the torch is then applied and the ends of the wires will fuse down to a round bead which shows almost no signs of oxidation.

The calibration of base-metal couples is usually carried out by direct comparison with a standard couple of the same type, or a platinum, platinum-rhodium couple. The question of checking large numbers of couples, such as is the problem in industrial plants, is well discussed in *Technologic Paper* 170 of the U. S. Bureau of Standards, from which the following is taken:

Standardization of Base-metal Couples.—It is difficult to secure equality of temperature between the hot junctions of two base-metal couples or between a base-metal and a rare-metal couple. One arrangement for precision calibration is to place the junction of the rare-metal couple in a small saw cut made in the hot junction of the base-metal couple and pinch the jaws of the saw cut until good thermal contact is secured. Small base-metal couples may be fused directly to the rare-metal couple. The rare-metal couple is protected by porcelain tubes to within a few millimeters of the hot junction, and the end of the porcelain tube is sealed to the couple by a small amount of kaolin and water-glass cement or by pyrex glass. This prevents contamination of the rare-metal couple, with the exception of the small length of 2 or 3 millimeters, which is necessarily exposed to the metal vapors. If the furnace is uniformly heated in this region a small amount of contamination will not cause any error. The method, however, is not feasible for work on a large scale. With fused or squeezed junctions the double potentiometer may be used in calibrating base-metal couples.

1. *Use of a Muffle Furnace.*—Several base-metal couples and the standard rare-metal couples mounted in non-porous porcelain tubes are packed together as closely as possible and tied into a bundle with asbestos cord. The hot junctions are inserted into a length of very heavy iron pipe capped at one end and the open end from which the couples protrude is tightly packed with asbestos wool. The iron tube and couples are mounted in the furnace and the e.m.f. measurements are made as soon as temperature equilibrium is reached. If the muffle furnace is large enough, the iron tubes protecting the base-metal couples need not be removed. A satisfactory size of furnace measures 8 by 8 by 30 inches deep. Precision work is impossible in this method of calibration. Even when every precaution is taken to reduce temperature gradients, differences in temperature of 10 or 20°C. frequently will be found to exist between the different couples mounted side by side. This accuracy, however, is sufficient for many industrial processes.

This method may be greatly improved by employing a large copper block drilled with holes into which the hot junctions of the couples are inserted. The heavy protecting tube is removed from each couple during the test.

2. *Use of Molten-metal Bath.*—A satisfactory method for calibrating base-metal couples on a large scale is by use of a bath of molten metal. An iron pot about 12 inches in diameter, or larger, and 15 inches deep is filled with tin or lead covered with powdered graphite. This may be heated in a gas furnace or an electric furnace wound with nickel alloy, such as nichrome or chromel. Into the tin bath dip about six iron tubes closed at the lower end and immersed to a depth of 12 inches. The tubes are just large enough to permit easy insertion of the

base-metal couple with its iron protecting tube. The standard couple is mounted in one of the six tubes and the base-metal couples are placed in the others. As soon as temperature equilibrium is reached the e.m.fs. are measured, that of the standard couple giving the temperature of the bath. A large number of base-metal couples may be tested one after the other at this temperature, and the process is then repeated at another temperature. The tin bath may be used satisfactorily in the range 300 to 1000°C., since tin is a metal of low volatility. Data obtained by the above method are plotted, temperature *versus* e.m.f., for each couple and a smooth curve drawn representing the calibration. For some types of base-metal couple, the curve is slightly S-shaped, showing small inflections near the critical points of the metals of which the couple is constructed. In precision work the calibration must be made at short-temperature intervals over these critical regions to determine the exact form of the temperature-e.m.f. curve.

3. *Single-point Calibration or Check Point.*—It is frequently desirable to check a base-metal couple at a single point. If the couple is reading e.m.fs., say 2 per cent higher at this temperature than the usual e.m.f. of that shown by the original calibration data, it is customary to assume that it reads 2 per cent high at all temperatures. This method of calibration at best is only approximate, and experimentally it is frequently found that a couple reading 2 per cent high at 800°C. indicates correctly at 1000°C. Single-point calibrations are of value, however, especially as a check upon the behavior of a couple in any particular temperature range.

A convenient standard temperature for this work is the melting or freezing point of sodium chloride (common salt), chemically pure. This material melts or freezes at 801°C. The salt may be used in a duriron crucible heated in a gas or electric furnace. The base-metal couples are immersed without protecting tubes from 4 to 6 inches in the bath. Melting or freezing point curves may be observed as already described. These curves are rather oblique on account of the low thermal conductivity of the salt, as discussed in the section on melting-point methods. The exact portion of the curve representing the true freezing point is reached when crystals begin to form along the entire length of the immersed end of the couple. The couple may be used as a stirring rod during the freezing. If the salt has not been previously fused, it must be melted the first time with a cover on the crucible as the imprisoned water in the salt crystals will cause the salt to sputter out badly. After the first melt, however, there will be no trouble in the use of this material. Molten salt reacts somewhat with most base-metal couples, but the reaction is so slow that the couple will not be injured. No serious change in the melting point resulting from heating the salt in contact with iron for several hours has been found.

4. *Checking Thermocouples in Fixed Installations.*—It is frequently desirable to check the readings of a thermocouple without removing it from the furnace in which it is installed. Tests of this nature are of extreme importance in the technical industries. They are also difficult to perform with precision, and the precision which is obtainable in a laboratory test cannot be expected in tests of this nature. An ordinary calibration in the laboratory of a base-metal couple which has been in use in a fixed installation for some time, while furnishing results apparently of high precision, does not, however, necessarily hold when the couple is returned to its original installation. This is on account of the heterogeneity developed in a base-metal couple after prolonged heating.

The presence of heterogeneity could be detected by a homogeneity test, but such tests on a large scale are not worth while for base-metal couples except for investigational work and, moreover, do not show how to correct the readings satisfactorily. Such a test would simply indicate that the couple should be thrown away, whereas in its permanent installation it still has a useful life. The throwing away of base-metal couples in a fixed installation as soon as heterogeneity sets up would be a very costly and unnecessary procedure, except in the comparatively rare cases where the highest possible accuracy is required. The degree of heterogeneity developed depends upon the type of installation, depth of immersion, location, and character of temperature gradient, etc. These quantities are fairly definite and fixed for any particular installation. If, however, the couple is removed from the installation and calibrated in the laboratory, these quantities are altered and the conditions under which the couple is actually operating cannot be reproduced. The calibration of the laboratory may give results quite different from the calibration which would be obtained if it were possible to duplicate exactly all the physical characteristics of the permanent installation. Hence, it is evident that if inhomogeneous couples are ever to be used, it is important that they be calibrated or checked in their fixed installation.

The exact method of procedure depends upon the type of installation. A standard checking couple is employed complete with a high-resistance galvanometer, "heat-meter," or portable potentiometer. The hot junction of the checking couple is placed as closely as possible to the hot junction of the couple under test, and the readings of the two couples compared. The main objection to the method is the difficulty in getting the two hot junctions together. One method is that of drilling a hole in the furnace at the side of each couple permanently installed large enough to permit insertion of the checking couple. The hole is kept plugged, except when comparison tests are being made. The checking couple is immersed in the furnace through this hole to the same depth as the

couple under test. The hole should be located as close to the permanently installed couple as possible.

In many installations the base-metal couple and protecting tube are mounted inside another protecting tube of iron, fire clay, carborundum, or some other refractory which is permanently cemented or fastened into the furnace wall. Frequently, there is room to insert a small test couple in this outer tube adjacent to the fixed couple. A third method, much less satisfactory, is that of waiting until the furnace has reached a fairly constant temperature and of making observations with the couple under test. Then remove this couple from the furnace, and insert to the same depth as the checking couple.

If desired, comparisons can be made preferably by either the first or second method at several temperatures, and a curve may be obtained for each permanently installed couple showing the corrections necessary to apply to its readings.

It may be thought that this method of checking couples is unsatisfactory, because in most furnaces used in industrial processes large temperature gradients exist and there is no certainty that the standard couple is at the same temperature as the couple under test. This objection, however, is not serious, because if temperature gradients do exist, in the furnace, of such a magnitude as to cause much difference in temperature between two similarly mounted thermocouples located near each other, the accuracy required by the measuring instruments need not be great, and the reading of the standard couple can be accepted for the standardization of the fixed couple just as satisfactorily as if the true temperature of the fixed couple were known. If temperature gradients exist of such a magnitude that two correctly calibrated couples similarly mounted near each other read, say, $20^{\circ}\text{C}.$ apart, it may be certain that neither couple is registering the temperature of material within the furnace to this degree of accuracy.



FIG. 13.—Thermocouple for use in molten metals. (Republic Flow Meters Co.)

It is often desirable to obtain the temperatures of molten baths of metal by means of thermocouples. It is unnecessary to use a welded couple in this type of service. Indeed errors may result if one is used. It is customary to insert the bare wires, held in a

3
3
3
2
1
A
suitable mounting, into the metal. A reading is taken quickly and the wires are immediately removed, for in some cases there is a decided reaction between the molten bath and the couple wires, which results in rapid disappearance of the thermocouple elements. Figure 13 represents equipment for temperature measurement of molten metals. The ease of replacement of the thermocouple elements is evident.

Multiple Thermocouples.—Where very small temperature differences are to be measured, it is sometimes expedient to use several thermocouples in series. Such an arrangement requires special calibration, since the e.m.f. per degree is much larger than if one couple is used alone.

INSTRUMENTS FOR MEASUREMENT OF E.M.F.

Instruments for the measurement of e.m.f. generated by thermocouples fall into three classes: (a) the galvanometer type, or millivoltmeter; (b) the potentiometer type; and (c) types involving a combination of the first two.

It is unwise to state that there is a marked superiority in any type of instrument. Attendant conditions which exist in various installations are of great importance when the selection of the type of indicating instrument is considered.

Millivoltmeters.—Most indicating instruments in use at the present time are of the millivoltmeter type. Several things are responsible for this fact: In most cases, this type of instrument is the least expensive; it was the first type to enter the field; and readings are taken by merely observing the position of an indicating needle, so that manual adjustments by inexperienced hands are unnecessary. Many different types of millivoltmeters are on the market, but the fundamental principle of operation is the same, the variations being in the construction and refinements of the instruments.

Principle.—All millivoltmeters operate on the d'Arsonval principle which involves a moving coil mounted between the

poles of a permanent magnet. This moving coil carries a long needle or pointer which swings over a scale graduated either in millivolts or temperature. Figures 14 and 15 represent one example of this mounting. In Fig. 15 is shown the detail of one of the pivots which support the coil. The cup in which the pivot revolves is cushioned on a delicate "shock-absorber" spring.

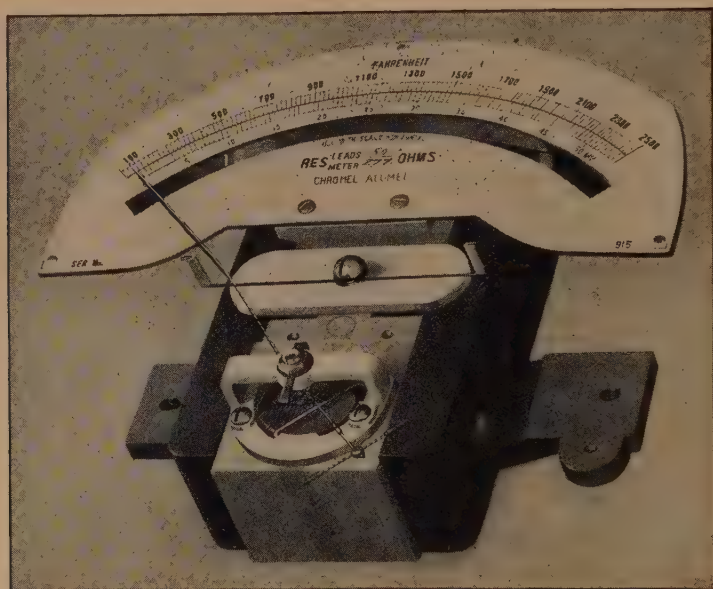


FIG. 14.—Millivoltmeter, showing scale and pointer mounting. (*Hoskins Manufacturing Co.*)

In some cases the coil is supported by regular galvanometer suspensions and in one or two cases the coil is supported by one pivot which is placed in the center of gravity of the whole moving system. If the pivot system is used, the jewel cups or bearings must be very carefully made in order that friction may be almost entirely eliminated. The movement of the coil and the needle are proportional to the thermoelectric current which passes through the coil and this current is proportional to the e.m.f. produced by the thermocouple. By the use of an internal series resistance and an extra binding post, it is possible to have the scale graduated for

both base- and noble-metal thermocouples. The coil turns against the resistance of a small spiral spring which returns the pointer to the zero position when the circuit is broken.

Resistance of Millivoltmeters.—It has already been pointed out that the e.m.fs. generated by thermocouples are very small, and it is easily appreciated that any millivoltmeter must be a

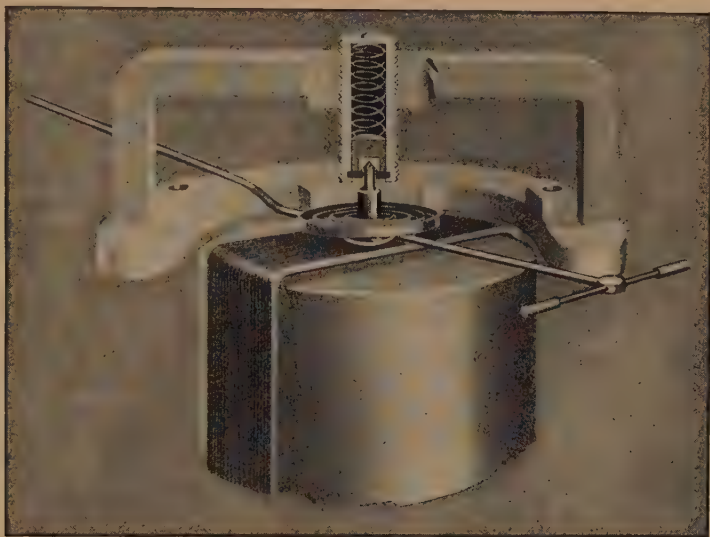


FIG. 15.—Pivot supporting coil in millivoltmeter. (*Hoskins Manufacturing Co.*)

comparatively sensitive instrument. Some of the earlier forms were so delicate that it was only with extreme care that they could be moved from place to place, and whenever they were used, it was necessary to level them carefully. As the use of thermoelectric pyrometers became wider, the construction of the instruments was made more robust, and it was possible to make them portable. As has already been stated, the turning moment of the moving coil is proportional to the current. If, therefore, the total resistance of the circuit is kept low, the current will be proportionally larger and it will be possible to build a sturdier instrument. As a result of this the early forms of portable millivoltmeters were all made with low total resistance. A good many of these are made and used today under well-controlled conditions.

One objection to the use of millivoltmeters lies in the fact that the e.m.f. indicated is less than the actual value developed by the couple, since the indicator requires that a current be delivered by the couple which would result in some fall of potential in the couple. This can be cared for by arbitrarily calibrating the scale to read the correct e.m.f. with a certain fixed line and couple resistance. If the line resistance varies, however, considerable error is introduced. These difficulties are all largely overcome if the millivoltmeter resistance is high, as will be presently demonstrated.

Assume that a millivoltmeter is graduated to read e.m.f. differences at its terminals. Let e_o represent the e.m.f. drop across the indicator; e the true e.m.f. of the couple; R_g the resistance of the millivoltmeter; R_c the resistance of the thermocouple; and R_1 the resistance of the leads. The relation between e_o and e is then

$$e_o = \left(\frac{R_g}{R_g + R_c + R_1} \right) e.$$

This expression follows from Ohm's law, which states that the e.m.f. drop between two points in a simple closed circuit is proportional to the resistance between the two points. It is very evident that, if R_g is large compared to R_c and R_1 , the ratio $\frac{R_g}{R_g + R_c + R_1}$ becomes nearly equal to 1 and the reading of the millivoltmeter does not differ much from the true e.m.f.

To illustrate, compare the behavior of millivoltmeters having resistances of 600 ohms and 10 ohms, respectively. The line and couple resistance is 2 ohms. Substituting in the above expression, it is found that in the case of the 600-ohm instrument $e_o = 0.996 e$, while in the case of the 10-ohm instrument $e_o = 0.830 e$. In the first case, the actual readings are only 0.4 per cent low, while in the second case they are 17 per cent low. The 600-ohm instrument might be used without arbitrary calibration, which would not be practicable for the 10-ohm instrument.

Assuming that both instruments are calibrated for a fixed external resistance, compare their behavior when line and couple

resistance vary. Let the line and couple resistance be represented by R' , the specific line and couple resistance for which the instruments are calibrated by R_o' , the reading of the instruments by e' , the e.m.f. of the couple by e , and the actual e.m.f. drop across the terminals of the instruments by e_o . It follows that when $R' = R_o'$, $e' = e$. The general relation between e' and e may be obtained as follows:

$$e_o = \frac{R_o}{R_o + R'} e, \quad (5)$$

or

$$e = \frac{R_o + R'}{R_o} e_o. \quad (6)$$

When $R' = R_o'$,

$$e' = \frac{R_o + R_o'}{R_o} e_o = e. \quad (7)$$

Substituting the general value of e_o in Eq. (5) in Eq. (7),

$$e' = \frac{R_o + R_o'}{R_o} \cdot \frac{R_o}{R_o + R'} e = \frac{R_o + R_o'}{R_o + R'} e. \quad (8)$$

Table III¹ represents the results computed from Eq. (8) when R' has values of 1, 2, 3, and 4 ohms, respectively, the value of R_o' being 2 ohms.

TABLE III

Line resistance in ohms	Error in indicated reading, per cent		Error in degrees at 1000°C.	
	600 ohms	10 ohms	600 ohms	10 ohms
1	+0.16	+ 9.1	+1.6	+ 91.0
2	±0.00	± 0.0	±0.0	± 0.0
3	-0.17	- 7.7	-1.7	- 77.0
4	-0.34	-14.3	-3.4	-143.0

¹ T. P. 170, U. S. Bur. Standards.

Variable line resistance is caused by a number of things, among which may be mentioned oxidation of the wire, poor contacts, variable depth of immersion, temperature variations in the line, and partial fracturing of lead wires.

Methods of Compensation for Errors Due to Line Resistance.

Use of Test Sets.—As long as a close check of the resistance in a

pyrometer circuit is maintained, it is entirely possible to use a millivoltmeter of low resistance. For this purpose, some form of Wheatstone bridge is necessary. By using this, increases of resistance may be detected and means taken for their elimination before any damage is done due to incorrect readings of millivoltmeters. It is advisable for any plant using millivoltmeter indicators having either high or low resistance to keep such a test set on hand, for by their use it is possible to locate breaks, grounds, or crosses in the circuits, as well as to detect variations in resistance. The location of faults requires a little more complicated arrangement of circuits, but full directions for such set-ups are usually included with the instrument.

The Use of Series Resistance.—In cases where it is known that there will be considerable variation in line resistance, it is possible to purchase millivoltmeters which carry a variable resistance in series with the moving coil. The instrument is originally calibrated to read correctly with a line resistance equal to the total resistance available in the contained rheostat. As the line resistance increases, the resistance in the instrument is gradually cut down. For instance, if such a millivoltmeter is calibrated to read correctly with a line resistance of 15 ohms and the actual line resistance is 5 ohms, the series resistance in the instrument will be reduced to 10 ohms. It is thus quite easy to keep the instrument reading correctly, providing the resistance in the line is frequently checked by means of a test set.

*The Harrison-Foote Method.*¹—It is troublesome to be using a millivoltmeter which requires constant checking of line resistance. Harrison and Foote have devised a method which eliminates the use of a separate instrument for the determination of line resistance. Figure 16 represents the wiring diagram of a millivoltmeter using this system of resistance compensation. G represents the moving coil. In series with G is an adjustable rheostat CB , with a maximum resistance equal to the maximum resistance which is

¹ HARRISON and FOOTE, *Jour. Am. Inst. Elec. Eng.*, Feb. 20, 1920.

liable to be found in the leads and thermocouple. The instrument is calibrated with this rheostat set at its maximum value. When the instrument is put into use, the rheostat must be adjusted until the sum of the resistances of the line L the thermocouple T and the portion of the rheostat r is equal to the maximum resistance of the rheostat, or r_5 , as it is represented on the sketch. The millivoltmeter is then operating with a total line resistance which is equal to the resistance in series with the galvanometer when it was calibrated. The reading is actually taken by adjusting the rheostat until the millivoltmeter reading is unchanged with the key K open or closed.

Let e_1 represent the e.m.f. drop from D to F when the key is open, e_2 the e.m.f. drop when the key is closed, and e the true e.m.f. of the couple. It follows then that

$$e_1 = \frac{er_3}{L + T + r_1 + r_2 + r_3}$$

and

$$e_2 = \frac{er_3r_4}{(L + T + r_1)(r_3 + r_4) + r_3r_4}$$

Equating these two expressions and solving for $L + T + r_1$,

$$L + T + r_1 = \frac{r_2r_4}{r_3}$$

If the three resistances r_2 , r_3 , and r_4 are proportioned during the manufacture of the instrument in such a way that $\frac{r_2r_4}{r_3} = r_5$, it is easily seen that the question of line resistance is eliminated by the procedure described above.

The Harrison-Foote method is used in the Brown improved heat-meter. Very satisfactory results have been obtained through the use of this instrument. It is particularly successful in cases where it is known that the thermocouple is to be subjected to very adverse conditions, or where there are great variations in the length of the lead wires.

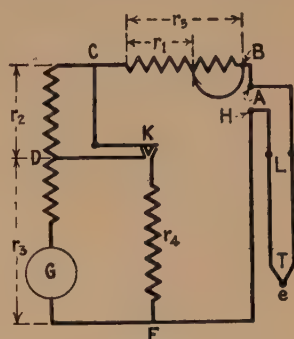


FIG. 16.—Diagram of circuits in millivoltmeter using the Harrison-Foote method of eliminating the effect of line resistance.

POTENTIOMETERS

Principle of Operation.—A potentiometer is a device for measuring potential differences by totally or partially balancing an unknown e.m.f. against a potential difference whose value is known through comparison with a known e.m.f. such as a standard cell. If the two e.m.fs. are exactly balanced, the instrument is called a zero or null-point potentiometer; if the e.m.fs. are only partially balanced and if the difference is indicated by a properly calibrated galvanometer, it is called a deflection potentiometer.

Figure 17 represents a simple potentiometer set-up, and by its use the principle may be demonstrated.

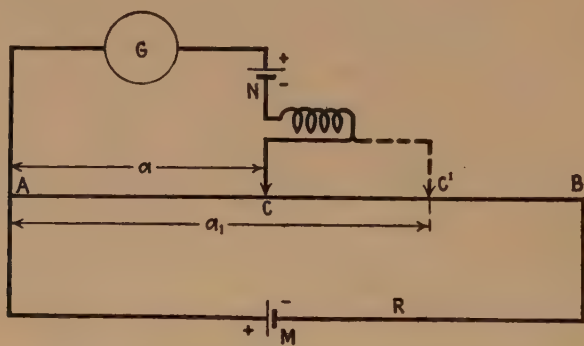


FIG. 17.—Diagram of slide-wire potentiometer.

AB represents a simple slide wire along which contact C is free to move. There is a potential drop from A to B due to battery M . For the present purpose it will be assumed that this drop is constant. It is easily seen that, provided the potential drop from A to B is greater than the unknown source of e.m.f., there will be some point C where the unknown e.m.f. is exactly balanced by the drop in the slide wire from A to C , and at which the galvanometer will register zero. Now, if E represents the unknown e.m.f., p the resistance per unit length of slide wire, a the distance AC , and i the current in AB , the following equation may be written:

$$E = api. \quad (9)$$

Next substitute for E a standard cell E_s , the e.m.f. of which is known. There will be some point C' at a distance a_1 from point A , where the galvanometer will again indicate zero. Then the equation may be written.

$$E_s = a_1 pi. \quad (10)$$

Dividing Eq. (9) by Eq. (10) and solving for E ,

$$E = E_s \frac{a}{a_1}$$

and the exact value of E may be ascertained.

If the potential drop from A to B could be maintained at a constant value, and the slide wire AB divided up into equal linear divisions, it would be possible to measure unknown sources of e.m.f. directly, since the linear distance from A to C would be exactly proportional to the potential drop between those points. It is possible to maintain a constant potential drop as mentioned above, if an adjustable rheostat is placed in the primary battery circuit, at point R , for instance, in Fig. 17. The procedure would then be as follows:

Insert a standard cell in the unknown e.m.f. circuit in place of battery N , and set the sliding contact at a value equal to the certified e.m.f. of the standard cell. This will, of course, cause a deflection of the galvanometer. Now adjust the rheostat R until the galvanometer is brought back to zero. When that is done, the e.m.f. drop over the slide wire will coincide with the graduated scale of the slide wire, and readings of unknown e.m.f.s. may be made directly. Unfortunately, the current in the slide wire does not remain constant for a great while, so that readjustment of the rheostat R against the standard cell is necessary at frequent intervals, while unknown e.m.f.s. are being measured.

The Portable Potentiometer.—Figure 18 illustrates the instrument board of the Leeds and Northrup portable potentiometer and Fig. 19 represents its wiring diagram. In this instrument the standard cell is connected over a portion of the main battery cir-

cuit, EF , whose resistance is made of such value that when the galvanometer is brought to zero by adjusting rheostat R , the voltage drop around dial G is, respectively, equal to the values in the scale on the slide-wire dial. This adjustment should be made at frequent intervals while using the instrument. Readings of unknown e.m.fs. are made by closing the thermocouple switch and adjusting sliding dial G until the galvanometer is brought to



FIG. 18.—Portable potentiometer. (Leeds and Northrup Co.)

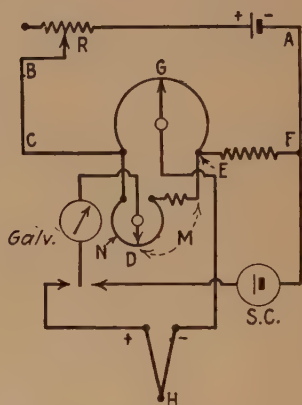


FIG. 19.—Wiring diagram of portable potentiometer. (Leeds and Northrup Co.)

zero. The graduations on the dial may be either in millivolts or temperature for a particular type of thermocouple.

The Precision Potentiometer.—In this instrument refinements of construction and operation have been introduced to such an extent that it is possible to read e.m.fs. to 0.001 and 0.0001 millivolt. It is used mainly for calibration of thermocouples and of less accurate instruments for the measurement of e.m.f.

SEMI-POTENTIOMETERS

The essential factor in the operation of a potentiometer is a constant current in the main battery circuit. By arranging the

wiring in a potentiometer in such a manner that the galvanometer may be thrown in on a shunt to the main battery circuit, it is possible to adjust this current to a predetermined proper value. The galvanometer is next thrown into the unknown e.m.f. circuit and used as a null-point instrument. This sort of an arrangement is not very satisfactory, but the same principle in modified form has been used successfully.

The Pyrovolver.—Figure 20 represents the wiring diagram of the Northrup pyrovolver. The use of this instrument involves two settings shown by diagrams 1 and 2 on the figure. In diagram 1,

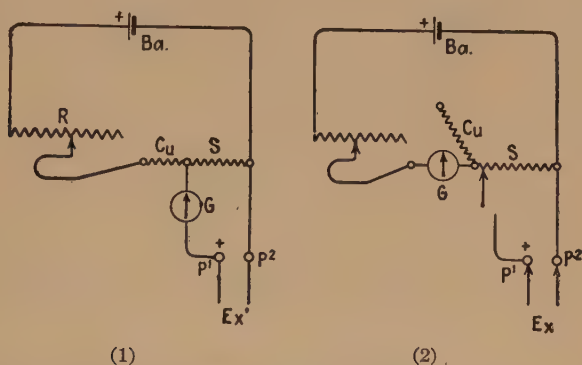


FIG. 20.—Circuits in instrument using Northrup's method. (*Pyroelectric Instrument Co.*)

is a battery B , a variable resistance R , a fixed copper resistance Cu (equal to the resistance of the moving element in galvanometer G), an accurate fixed manganin resistance S , and the galvanometer G . The unknown source of e.m.f., usually a thermocouple, is connected at Ex . The galvanometer in this setting serves as a null-point instrument in determining when a balance is established between Ex and the drop in potential across S , which is varied by means of rheostat R . This balance having been obtained, a button is depressed which changes the system to the form shown in diagram 2. The galvanometer G is here substituted for the resistance Cu which has resistance and temperature coefficients equal to that of the galvanometer. The galvanometer will therefore deflect proportionally to the current which is flowing through S , and its

scale may be marked to indicate the e.m.f. drop across S . The e.m.f. across S , however, was made equal to that of the unknown source in operation 1, so the galvanometer is indicating the amount of the unknown source of e.m.f. By changing the value of S to other fixed values, additional ranges are given.

Northrup's method may be applied to continuously deflecting instruments by the addition of an extra key switch and a rheostat. After the e.m.f. of a thermocouple has been determined as described in the preceding paragraph, the galvanometer is connected in series with the extra resistance and the thermocouple. The extra resistance is then varied until the reading of the galvanometer is the same as when the e.m.f. was determined by the pyro-volter. In this way variations in line and couple resistance may be compensated.

DEFLECTION POTENTIOMETERS

The objection is sometimes made that the null-point potentiometer is unsatisfactory as a shop instrument on account of the fact that a manual adjustment is required before the instrument can be read. This objection is very nearly met by the deflection potentiometer,¹ which may be constructed so as to include the accuracy of the regular null-point potentiometer and the ease of reading of a millivoltmeter.

In the deflection potentiometer only part of the e.m.f. of the thermocouple is balanced against the resistance through which the main battery current is flowing. The remaining portion of the e.m.f. is indicated by a galvanometer which is in series with the thermocouple. For instance, the instrument might be constructed in such a way that a dial would indicate whole millivolts and a galvanometer would indicate fractions of millivolts. Figure 21 represents the simple wiring diagram of a deflection potentiometer. AC is a slide wire along which contact D moves.

¹ For mathematical deduction of the theory of the deflection potentiometer by Brooks, see *Bur. Standards, Sci. Papers* 33, 79, 172, 173.

The points on AC represent integral e.m.f. drops or the corresponding number of degrees of temperature. G is the galvanometer which indicates the fractional parts of the divisions on the slide wire.

It can be shown that correct readings of the galvanometer are only obtained when the sum of the resistances of the galvanometer, the thermocouple, and the potentiometer are constant. This is not the case, since it is necessary to vary the dial settings on the potentiometer from time to time. In order to compensate this error, a variable resistance is placed in the galvanometer circuit—

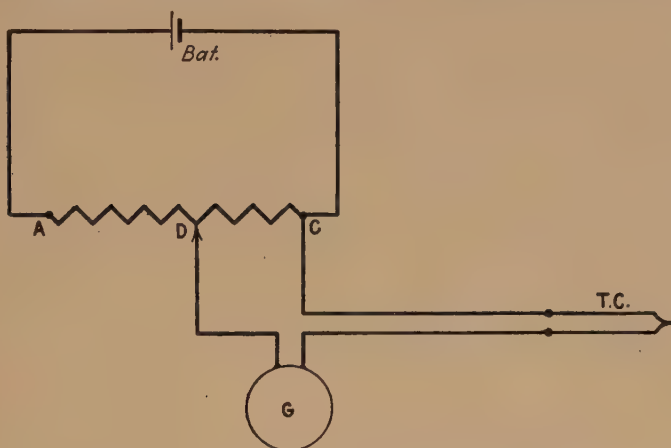


FIG. 21.—Simple circuits in deflection potentiometer.

in some instruments it is made an integral part of the dial—so that turning the dial adjusts the e.m.f. setting and at the same time adjusts the compensating resistance in the galvanometer circuit.

THE COLD-JUNCTION CORRECTION

As has been previously stated, it is very necessary that the cold junction of a thermocouple be at the temperature for which it was calibrated. As soon as there is a departure from this temperature, the readings of the indicator are incorrect, unless some means of compensation are employed. In the case of simple installations, it is possible to obtain the true temperature at the hot junction by adding to it a value obtained by multiplying the difference between the actual cold-junction temperature and the correct cold-junction

temperature by a factor K which depends upon the type of couple being used and the temperatures of the hot and cold junctions. The factor K varies from 0.3 to 1.5, but for general purposes may be taken as 1.0 for base-metal couples and 0.5 for noble-metal couples. The variation in K depends upon differences in slope at low temperatures of the temperature-e.m.f. curve.

Most instruments for the measurement of the e.m.f. of thermocouples are provided with some sort of device for cold-junction error compensation. Some of these require setting by the operator and some are automatic. In any event, it is much more desirable to maintain the cold junction at as near a constant temperature as possible. One method for accomplishing this is to jacket the head of the couple and maintain a circulation of tap water around it. This method is cumbersome and very little used. It is evident that if the couple were made of sufficient length it would be possible to carry the cold junction well away from the furnace and provide some means for maintaining it at a fairly constant temperature. It is not practicable nor advisable to make such a long couple in single sections, so recourse is had to so-called "compensating leads." In most cases these leads are multiple-strand, flexible wires made from the same material as the corresponding thermocouple elements. The leads are tightly attached to the elements of the couple proper and extend from there to the cold junction, which may be either at the indicating instrument or at some particular point where the temperature remains nearly constant. In the case of noble-metal couples, it is too expensive to use such leads, but the difficulty is partially offset by the use of Bristol compensating leads which consist of a copper wire and a copper-nickel alloy wire. The copper wire is attached to the platinum-rhodium element of the couple and the copper-nickel wire to the platinum wire of the couple. These leads may be actually termed compensating leads.

Among the methods used for maintaining a constant cold-junction temperature, the use of a thermostatically controlled

chamber and the placing of the cold junction underground may be mentioned. The idea of a thermostatically controlled chamber needs no discussion. The temperature at a depth of 10 feet underground remains constant within $\pm 2^{\circ}\text{C}$. in most localities the year round. An iron pipe closed and pointed at the bottom is driven into the ground and the two cold junctions, well insulated, are inserted in the top of the pipe and pushed down to the bottom. They must, of course, be well soldered to the copper leads which convey the e.m.f. to the indicating instrument. It follows that there are four wires in the pipe—the two compensating lead wires coming from the couple and the two copper leads going to the instrument. It is well to have some means of determining the temperature at the bottom of the pipe, so that adjustments of the indicator may be made for any variations which occur.

Millivoltmeter Compensation.—In the case of millivoltmeters there is a zero adjusting screw which makes it possible to move the needle to any desired point. If, therefore, the cold-junction temperature is known, it is only necessary to move the needle to this temperature, or the e.m.f. corresponding to it, while the instrument is on open circuit. As long as the cold-junction temperature does not vary, the indicated readings will be correct. Any variation of the cold-junction temperature however, means a new adjustment of the needle. The Bristol compensator makes this adjustment automatically through the use of a bimetallic spring, and a good many of the millivoltmeters now on the market include this feature. The metals in this spring possess different coefficients of expansion, so that as the temperature varies the spring tends to coil or uncoil, thereby moving the galvanometer needle to the new position. In order to make use of this compensation, the cold junctions of the couple should actually be at the instrument.

Potentiometer Compensation.—Figure 19 represents the wiring diagram of the Leeds and Northrup portable potentiometer equipped with a manually operated, cold-junction compensator. The e.m.f.

generated by the thermocouple, or its corresponding temperature, is indicated on the main dial at point *G*. In parallel with the main slide wire is a smaller one on which point *D* is indicated. These two slide wires, with the galvanometer, form a typical Wheatstone-bridge circuit. If the cold-junction temperature is at the zero point of the e.m.f. scale, point *D* is placed at zero and readings are made directly by moving point *G* to the proper position. If, however, the cold junction varies, point *D* is placed at a value

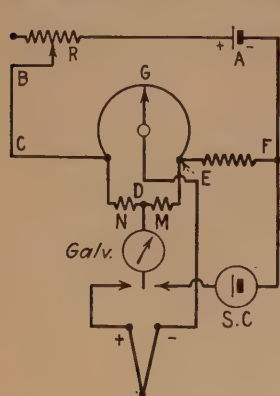


FIG. 22.—Wiring diagram of automatic cold junction compensator. (Leeds and Northrup Co.)

representing the departure from the calibrated cold junction. This requires a new setting of point *G* to maintain the galvanometer at zero. In this way the proper hot-junction temperature will be indicated, although there may be variations in e.m.f. due to variations in the cold-junction temperature.

The idea just described has been applied in an automatic compensator whose wiring diagram is shown in Fig. 22. Here the contact *D* is fixed between two resistances, *M* and *N*. *M* has a zero temperature coefficient of resistance while *N* has a high temperature coefficient. The resistance *N* is located close to the cold junction of the couple, so that its temperature variations are the same as those of the cold junction. When the cold-junction temperature rises, the e.m.f. of the couple decreases, but the resistance of *N* increases, which is equivalent to moving point *D* in Fig. 19. If *M* and *N* are properly proportioned, it is not difficult to secure very satisfactory compensation by this means.

Compensation by Means of a Shunt.—Figure 23 illustrates the use of a shunt across the terminals of a thermocouple as a means of securing partial compensation for the cold-junction error. As the cold-junction temperature increases, the e.m.f. of the couple decreases, but at the same time the resistance of the shunt increases,

which causes a slight increase in the potential drop across the shunt. It is better to use a potentiometer for measuring e.m.f. if a shunt is used, for the presence of the shunt causes a decrease in the current which would pass through a millivoltmeter if it were used as a means of e.m.f. measurement. Millivoltmeters, of course, may be used, but they have to be of special construction.

Compensation by Means of a Wheatstone Bridge.—Figure 24 represents the wiring diagram for cold-junction compensation in

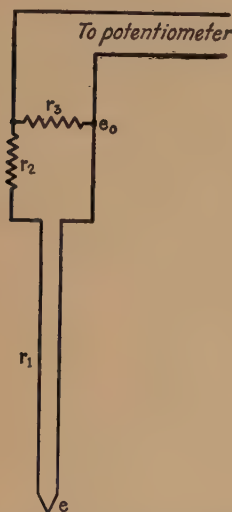


FIG. 23.—Wiring diagram of shunt method of cold junction compensation. (T. P. 170. U. S. Bur. Stand.)

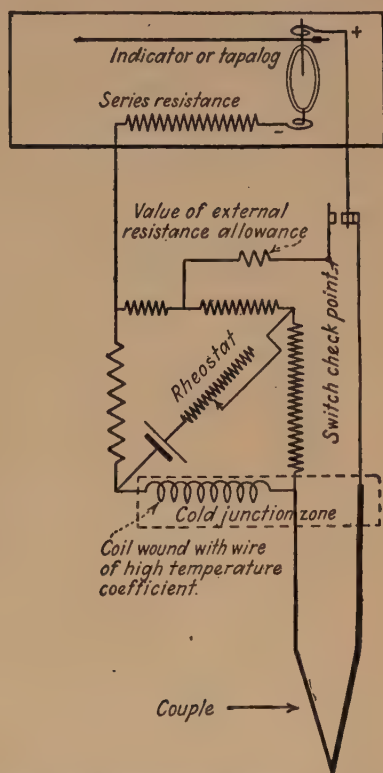


FIG. 24.—Wheatstone bridge method for cold junction compensation. (Wilson-Maeulen Co.)

indicators produced by Wilson-Maeulen Company. The Wheatstone-bridge circuit in one of the lines is easily identified. Three arms of the bridge are made of manganin wire, while the fourth, which is in the cold-junction zone, consists of nickel wire which has a high temperature coefficient. The cold junction of the couple is brought to the instrument by means of compensating leads. As the cold-junction temperature varies, the resistance of the coil of

nickel wire varies in such a manner as to vary the balance over the Wheatstone bridge, with the result that more or less e.m.f. is impressed over the millivoltmeter, depending on whether the cold-junction temperature rises or falls. The compensation is dependent upon the constancy of the current flowing in the arms of the bridge, thus making a preliminary setting necessary. This is accomplished by closing the switch at the check point and adjusting the rheostat until the millivoltmeter needle swings to a given point on the scale. This setting has to be checked occasionally.

Use of a Junction Box.—In large installations of thermoelectric pyrometers, the location of cold junctions becomes somewhat of a

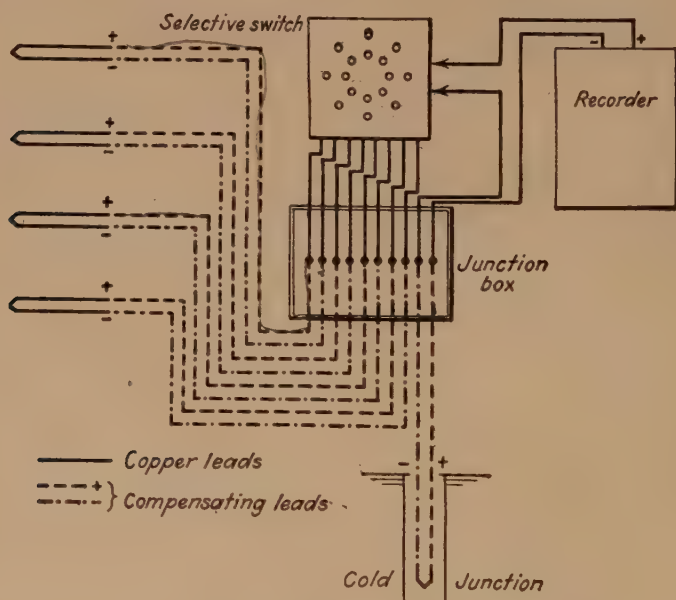


FIG 25.—Wiring diagram of installation using junction box. (T. P. 170. U. S. Bur. Stand.)

problem. If the cold junctions were all located at the instruments and the instruments were all assembled in one locality, the cost of compensating leads would be very high. In order to eliminate this large amount of compensating leads, a so-called junction box is sometimes used. The wiring diagram is shown in Fig. 25. The

box is made of heavy metal in order that the temperature within may remain practically constant.

The buried cold junction in this case is not the actual cold junction of the thermocouples which may be switched into circuit with it, but is the cold junction of an auxiliary couple whose hot junction is in the junction box. It will be seen that the actual cold junctions of the couples are in the junction box and that if the temperature of the junction box rises their e.m.f. will drop. The rise in temperature of the junction box, however, increases the

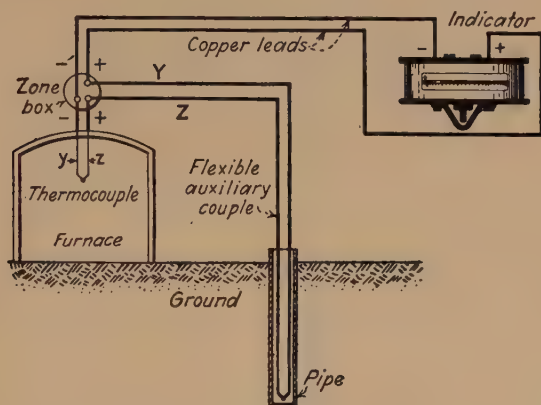


FIG. 26.—The zone box installation. (Wilson-Macaulen Co.)

e.m.f. of the auxiliary couple, and this being connected in the circuit in such a way that its e.m.f. is additive, impresses into the circuit enough e.m.f. to just compensate for that which is lost in the main thermocouple circuit by the rise in temperature of the junction box.

By means of this installation it is possible to locate the indicator or recorder at any distance from the furnaces, using only one set of copper leads.

The Zone Box.—The principal of the zone box (Fig. 26) is similar to that just described in the junction box, except that the connection of the furnace couple to the auxiliary couple is permanent. A detailed explanation is therefore unnecessary. The

use of the zone box makes it unnecessary to run the copper leads to the buried cold junction.

THERMOELECTRIC PYROMETER INSTALLATION

A brief consideration of some points in connection with the installation of thermocouple systems may not be out of place. One thing which should always be kept in mind is the fact that the e.m.fs. and the currents generated by thermocouples are small and, therefore, the resistance of the lines should be kept at the lowest figure possible. Nothing smaller than No. 12 copper wire should be used, and switches should have a much higher ampere rating than the value of the current in the line indicates unless the potentiometer is used. 100-amperes switches are sometimes to be desired.

A couple placed in one corner of a large furnace may not give anything like an adequate indication of the average temperature of the furnace. It is hard to give any rules for procedure, but a good rule to follow is to place the hot end of the couple as near the work as possible and near a point where average temperature conditions exist. In large furnaces it is better practice to use two or more couples. In this way the temperature at more than one point is obtained and better control is possible. Some furnaces have a couple in each corner and one in the middle. This makes possible the production of a very even temperature throughout the furnace chamber if each couple actuates a correspondingly situated heating element.

The length of the couple which lies within the heated zone is of great importance. This is sometimes called the "depth of immersion." If a couple is insufficiently immersed, conduction to the outer, cooler sections is so high that the reading of the couple will be low. It is good practice to insert the couple just as far as possible. This will insure satisfactory results as a rule, but in cases where it is suspected that the immersion is not sufficient, the temperatures along the protecting tube should be explored and if

there is a sudden drop near the hot end of the couple, means should be taken to produce a sufficient immersion.

Some couples are purposely immersed an insufficient distance (see Fig. 9). This is done when the temperature of the furnace is

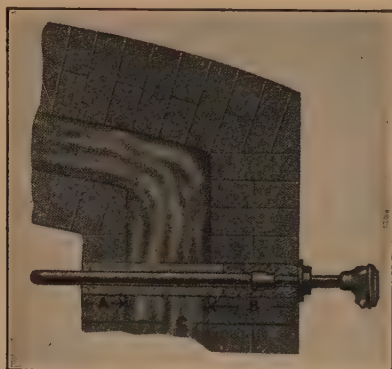


FIG. 27.—Thermocouple installed in a muffle furnace. (*Republic Flow Meters Co.*)

so high that there is danger of fusing the couple and tube. Although the temperature read is low, it is possible, by correlation with physical changes of material within the furnace, to obtain a fairly accurate idea of the temperature for future operations.

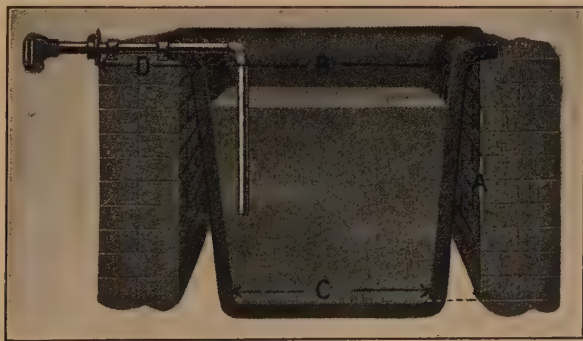


FIG. 28.—Thermocouple installed in a lead pot. (*Republic Flow Meters Co.*)

Figures 27 and 28 represent typical installations of thermocouples. In Fig. 27 the couple is shown placed in a muffle furnace. The hot end is sufficiently immersed and the portion going through the muffle is protected by a sleeve. Figure 28 shows a right-angle installation of a thermocouple in a lead pot.

When a gas is passing through a flue or furnace its actual temperature is not indicated by a thermometer or thermocouple placed in the gas stream unless the walls are at the same temperature as the gas. Even if there is considerable difference between the temperatures of the walls and gas stream, a condition of equilibrium will be reached and the thermometer or thermocouple will indicate a temperature somewhere between the temperatures of the walls and gas. This is due to radiation of heat from the walls to

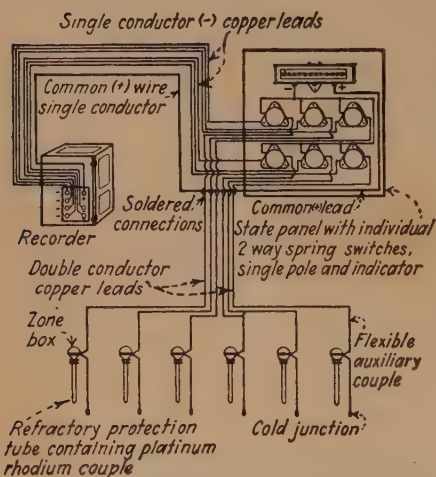


FIG. 29.—Thermocouple installation using common lead wire. (Wilson-Maeulen Co.)

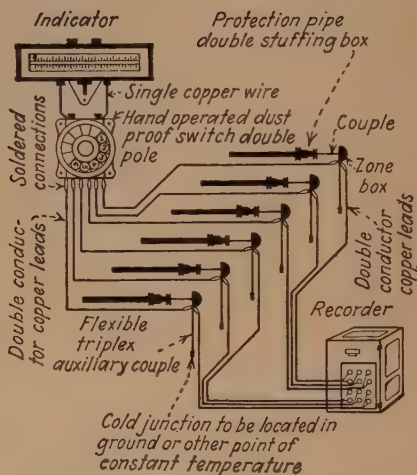


FIG. 30.—Thermocouple installation using individual lead wires. (Wilson-Maeulen Co.)

the temperature-measuring instrument and to a loss of heat by the instrument to the surrounding gas, by convection. Suitable correction¹ for this condition should be made.

Figures 29 and 30 represent two types of wiring which are used in installing a thermoelectric pyrometer system. The relative positions of the parts of the system are also clearly shown. Figure 29 illustrates the use of the so-called common lead. All the positive terminals of the thermocouples are connected to a com-

¹ See WALKER, LEWIS, and McADAMS, "Principles of Chemical Engineering," pp. 165-167.

mon lead wire which is connected to the indicator and recorder. The objection to this type of wiring lies in the fact that if the common lead is broken or short-circuited, the whole system is thrown out of operation. While it is economical of lead wire, it is not usually recommended. Figure 30 shows the individual lead wire system where each couple has its own leads to the recorder. If anything happens to a lead wire in this case, only one couple is affected and much inconvenience eliminated.

EXPERIMENT 1

OBJECT: To study the Peltier effect.

If an e.m.f. exists at the contact surface of two dissimilar metals, then a current passed in such a way as to oppose this e.m.f. would produce heat at a greater rate than the ordinary power expression RI^2 . If passed in the reverse direction, a cooling effect might be expected if the heat withdrawn from the junction is greater than the RI^2 liberated.

Cross a short iron wire with a constantan wire and fuse together. Antimony and bismuth or many other pairs of metals would do as well. Connect this thermal cross to a battery supply through a reversing switch. Connect the other terminals of the thermocross so that by means of a double-throw switch the heating current is broken and a galvanometer is connected to the junction. Observe the deflection of the galvanometer with the reversing switch in each position. Vary the value of the current and the time of heating. Explain results.

EXPERIMENT 2

OBJECT: To observe the Thomson effect in metals.

Arrange a differential thermocouple along a metal conductor, by drilling two small holes about 10 centimeters apart and inserting the junctions of the couple so that they are insulated from the metal conductor (see Fig. 4). About halfway between the junctions, arrange an electric heater of a few turns of resistance wire, so that it may be moved along the conductor. Slide the heater along the conductor until the galvanometer connected to the differential couple shows no deflection. Now pass a current of a few amperes through the conductor and observe the galvanometer. Reverse the current and note the effect. Explain results.

EXPERIMENT 3

OBJECT: Determination of the e.m.f.-temperature relationship of a copper-iron thermojunction.

Procure a 2-foot section each of No. 14 copper and iron wire.

Construct a thermojunction of these two by twisting the ends together and fusing in the electric arc, or an oxy-gas flame.

Attach to this junction the hot junction of a calibrated chromel-alumel or iron-constantan couple, and place the combined junctions in a furnace whose temperature may be rapidly and easily varied. A small electric resistance furnace is best for this purpose. The chromel-alumel or iron-constantan couple in conjunction with a suitable indicator is used to determine the temperature of the two hot junctions.

Immerse the cold junctions in a thermos bottle containing cracked ice, and connect each couple to a millivoltmeter or potentiometer. Gradually raise the temperature of the furnace and take simultaneous readings of temperature and e.m.f.

Plot the e.m.f.-temperature curve of the iron-copper couple and fit it with an equation. Solve for the constants.

EXPERIMENT 4

OBJECT: Calibration of a platinum, platinum-rhodium thermocouple by the use of fixed temperature points.

The fixed points required in this calibration are the melting points of zinc, aluminum, and copper. Samples of these metals, with certified melting points, may be obtained from the U. S. Bureau of Standards.

The crucibles used should be of such size as to hold conveniently 50 cubic centimeters of molten metal, this being a convenient amount of metal to use with the ordinary sizes of noble metal thermocouples.

The sample of metal is first melted. In doing this the crucible should be heated in such a device (either a gas or electric furnace) that a layer of fine graphite can be maintained over the top of the crucible and the surface of the metal. The apparatus, shown in Fig. 86, Chap. VIII, is particularly well adapted to this calibration. The top of the crucible should have a hole of suitable size for the introduction of the protecting tube of the couple. The protecting tube should be of glazed porcelain or fused quartz.

After the metal has become molten, carefully insert the protecting tube without the couple. Care must be exercised or the protecting tube will be broken. After the tube has been successfully lowered into the molten metal, the couple may be inserted in the protecting tube. The cold junction of the couple should be packed in a thermos bottle containing cracked ice. As the metal cools, take e.m.f. readings at intervals of 15 seconds, and prepare a curve of e.m.f. *versus* consecutive time. There will be a halt in this curve at the freezing point

of the metal. Calculate the average e.m.f. during this halt. As soon as the metal is nearly solid, remove the couple and protecting tube.

The above procedure is carried out with each one of the three metals.

The e.m.f.-temperature relation for the couple is represented by the equation

$$e = a + bt + ct^2,$$

$$e = \text{e.m.f.},$$

$$t = \text{temperature of hot junction of couple.}$$

$$a, b, \text{ and } c \text{ are constants.}$$

Since e was determined at three temperatures, it is possible to determine a , b , and c by solving the three simultaneous equations.

In this manner, determine the final equation for the couple that is being calibrated.

EXPERIMENT 5

OBJECT: Effect of cold-junction temperature upon the e.m.f. of a thermocouple.

Fasten together the hot junctions of two platinum, platinum-rhodium thermocouples. Place their cold junctions in separate thermos bottles filled with cracked ice. One of the couples is used merely to obtain the correct temperature, but any other carefully calibrated thermocouple will serve this purpose. Place the attached hot junctions in a furnace whose temperature may be easily and quickly varied. Obtain the data necessary to plot an e.m.f.-temperature curve for the platinum, platinum-rhodium couple over the range from 0 to 700°C. Repeat over the same range but maintain the cold-junction temperature at 30°C.; at 60°C. This may be done by carefully heating a 500-cubic centimeter beaker of water into which the cold junction is placed.

The first curve obtained is the one usually found in tables. Suppose this couple were being used with such a table, but with the cold junction at some other temperature, $t^\circ\text{C}$. The true temperature T would be

$$T = \text{indicated temperature} + Kt.$$

Evaluate K from the data, showing that it is not a constant. How does it vary with cold- and hot-junction temperatures?

When K is greater than 1, what must be the slope of the e.m.f.-temperature curve at low temperatures?

Problems

1. The hot junction of a thermocouple is at a temperature of 500°C., the cold junction at 0°C. At a point midway between the hot and the cold junction, the couple wires are heated to a temperature of 750°C. Neglecting

conduction of heat along the wires, what temperature will be read on the indicating instrument? Using a diagram, demonstrate the reason for the answer given.

2. The hot junction of a copper-constantan thermocouple 3 feet long is at a temperature of 500°C ., the cold junction is at 0°C . At a point on the positive wire midway between the two junctions a 4-inch section is cut out, and a 4-inch section of brass wire welded in its place. If both junctions of the brass wire are at 25°C ., what will be the effect on the temperature shown on the indicator? What will be the effect if one brass junction is at 50°C . and the other at 25°C . Using diagrams, demonstrate in terms of relative e.m.f. the reasons for the answers given.

3. The hot and cold junctions of a thermocouple remain constant. If the resistance of couple and leads changes from 2 to 3 ohms, the e.m.f. across the millivoltmeter drops 0.2 per cent. Calculate the resistance of the millivoltmeter.

4. The resistance of thermocouple and leads is 2 ohms. The resistance of the millivoltmeter is 300 ohms. Calculate the increase in couple and lead resistance which will cause a drop of 1 per cent in e.m.f. across the millivoltmeter.

5. A millivoltmeter with a resistance of 15 ohms is calibrated to read correctly when couple and lead resistance equals 3 ohms. If couple and lead resistance drops to 2 ohms, calculate the per cent error in readings of the millivoltmeter.

6. A thermocouple has its cold-junction variations compensated by means of a shunt. The resistance of the couple and leads is 60 ohms, while the resistance of the shunt is 100 ohms. Assuming the hot junction remains constant, calculate the increase in resistance of the shunt which will just compensate for a drop of 0.2 per cent in the millivoltage indicated by the potentiometer.

7. The resistance of a thermocouple and its leads is 3 ohms. The hot junction remaining constant, the e.m.f. of the couple is read successively by a potentiometer and a millivoltmeter. The potentiometer indicates 25 millivolts, while the millivoltmeter indicates 24.2 millivolts. Calculate the resistance of the millivoltmeter.

8. A thermocouple having a resistance of 0.4 ohm is connected through leads of a resistance of 1.5 ohms to a recording millivoltmeter with a resistance of 300 ohms. An indicating millivoltmeter is later to be connected in parallel with the recorder. What resistance must the indicator have in order that the readings of the recorder shall not be in error more than 1 per cent?

9. The chromel wire of a chromel-alumel couple has a resistance of 0.0828 ohm per foot. The resistance of the alumel wire is 0.0432 ohm per foot. The corresponding compensating lead wires have the same resistance per foot as the couple wires. How far away (distance measured along the wires) from the hot

junction of the couple can a millivoltmeter with a resistance of 200 ohms be placed, in order that the error in its readings will not be over 1 per cent?

10. A thermocouple with a resistance of 0.25 ohm is connected to a millivoltmeter 500 feet away (distance measured along the wires) by leads of No. 18 copper wire which has a resistance of 0.0059 ohm per foot at 0°C . and 0.0065 ohm per foot at 25°C . What must be the resistance of the millivoltmeter, in order that the error in its readings will not be greater than 0.5 per cent, as the temperature varies from 0 to 25°C .?

11. An indicator and a recorder, each having a resistance of 100 ohms, are connected in parallel. The line and couple resistance is 3 ohms. Calculate per cent error in reading of the two instruments.

12. A copper-constantan couple is calibrated with its cold junction at 0°C . What e.m.f. will be read from the thermocouple if the hot junction is at 500°C ., and the cold junction at 25°C .? (See tables in appendix.)

13. A chromel-alumel couple is calibrated in degrees Fahrenheit with its cold junction at 75°F . What correction will have to be made to the indicated e.m.f. of the couple if the cold junction is actually at 45°F .? (See tables in appendix.)

CHAPTER IV

RESISTANCE THERMOMETERS

Resistance-temperature Relations.—Measurements upon the electrical resistance of a metallic conductor as the temperature of the conductor is increased indicate that the resistance increases with the temperature. The relationship between resistance and temperature, as measured by the gas thermometer, is in general not linear such as might be represented by the equation

$$R = A' + B'T \quad (1)$$

but is closely expressible by an equation of higher degree, such as

$$R = A + BT + CT^2. \quad (2)$$

The dependence of R upon T should be explained by any satisfactory theory of electric conduction. On the basis of the free electron theory, Drude¹ obtained the following expression for the electrical resistivity ρ of a metal; $\rho = \frac{aT}{Nlu}$, a being a constant, N the number of free electrons per cm.³, l the mean free path of the electrons, and u their average velocity at the temperature T . As T increases, N and u must increase while l probably decreases.

If a resistance coil be constructed and its resistance measured at certain known temperatures, then the resistance at other temperatures might be used to measure those temperatures. This device is called a "resistance thermometer." Its use was first proposed by Siemens² in 1871. It was at first thought that the relative change in resistance per degree (called the temperature coefficient of resistance) for all pure metals was the same at the temperature 0°C. Some 15 of the common metals have an average

¹ Ann. Phys. vol. 1. p. 566, 1900.

² Proc. Royal Soc., vol. 19, p. 351, 1871.

value of 0.0039 for this coefficient, but individual values vary by as much as ± 0.0005 from this amount. As the metal platinum does not readily oxidize at high temperatures and as it has a relatively large and uniform change in resistance with temperature over a wide temperature range, it is used extensively as the resistor material in thermometers of this type. Nickel is sometimes used for work at lower temperatures and palladium may be used at temperatures as high as 600°C .

In the early coils made by Siemens¹ the platinum wire was wound on a pipe-clay tube and the coil placed in an iron protecting tube. When heated to a high temperature, the platinum was changed in resistivity due to some chemical action provoked by the presence of the clay. For this reason this method of temperature measurement was in ill repute until 1886 when it was revised by Callender who sealed the platinum coil within the bulb of an air thermometer and demonstrated its reproducibility with continued heating and cooling.

Platinum Temperature.—If the resistance of a coil of platinum wire be measured when placed in melting ice and when placed above water boiling under standard conditions of pressure, the values obtained, designated, respectively, as R_0 and R_{100} , may be represented on a resistance-temperature diagram. A straight line through these points, shown by curve *A* in Fig. 31, whose equation is $R_t = R_0(1 + \alpha_0 T)$ would then represent the relationship between R and T if the change in R was proportional to the change in T . The constant α_0 is called the zero temperature coefficient of resistance and is given by the expression $\frac{(R_{100} - R_0)}{100R_0}$. For pure platinum, it has a value of 0.003915. Thus, any unknown temperature which would cause the thermometer to have a resistance R_t would be $T_{pt} = \frac{(R_t - R_0)}{\alpha_0 R_0}$. Temperatures found in this way are called platinum temperatures and are, of course,

¹ *Loc. cit.*

not correct, since a linear relationship between R and T does not exist. The actual relationship between R and T for platinum is shown in curve B in Fig. 31. For pure platinum this curve is closely represented by the following equation:

$$R_t = R_0(1 + \alpha T + \beta T^2)$$

in which $\alpha = +0.00392$ and $\beta = -0.000000588$.

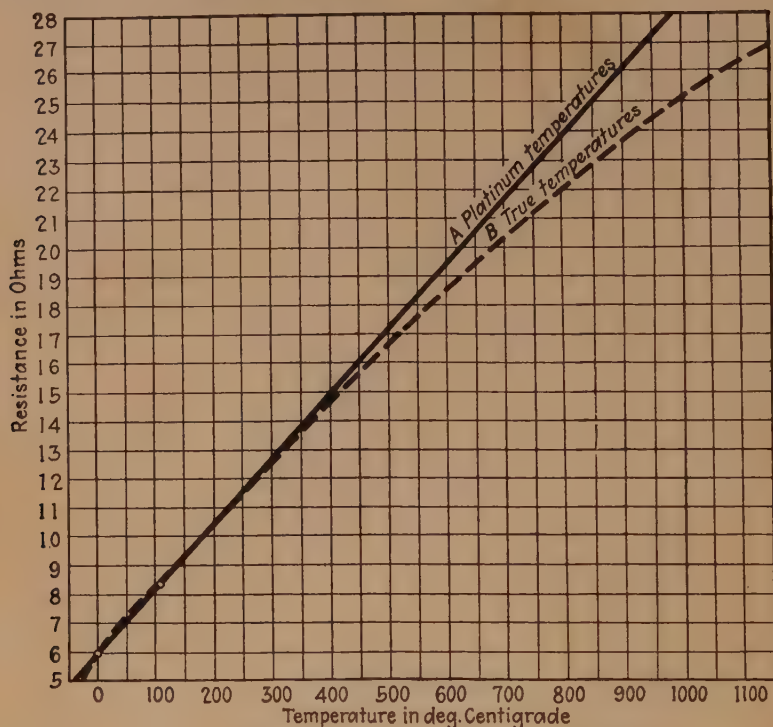


FIG. 31.—Resistance-temperature curves for platinum.

It is thus evident that between 0 and 100°C. the platinum temperature is greater than the true temperature, while above 100°C. it is less. To find experimentally the values of α , β , and R_0 , an additional fixed temperature must be included in the calibration. For this purpose the boiling point of sulphur under conditions of standard pressure 444.6°C. is generally used. The correction to be applied to the sulphur boiling point on account of pressure is

$$T_{m.P.} = 444.6 + 0.0908(P - 760) - 0.000047(P - 760)^2.$$

Callendar's Correction.—Callendar¹ suggested that since it is easy to obtain the platinum temperature T_{pt} , it would be convenient to obtain an expression for the difference between the true and the platinum temperatures for any value of the platinum temperature. The value of the resistance at any true temperature T is $R_t = R_0(1 + \alpha_0 T_{pt}) = R_0(1 + \alpha T + \beta T^2)$. At the boiling point of water, $T = T_{pt} = 100$, giving $\alpha_0 = \alpha + 100\beta$. Substituting this value of α in the equation above gives

$$T - T_{pt} = \frac{-(100)^2\beta}{\alpha_0} \left\{ \frac{T^2}{100^2} - \frac{T}{100} \right\} = \delta \left\{ \frac{T^2}{100^2} - \frac{T}{100} \right\}$$

The value of δ is found to be about 1.5, varying somewhat with the purity of the platinum. Thus, the value of the correction to be added to the platinum temperature to obtain the true temperature at 50°C. is about -0.4° , while at 400°C. the correction is about $+20^\circ$ C. Table IV, on page 72 gives this correction value for a particular thermometer over a wide temperature range. Since T enters in the equation and not T_{pt} , the difference may first be found using T_{pt} . Then this value may be used to revise T_{pt} and substituted again in the formula to get a closer value of $T - T_{pt}$. Callendar and Griffiths² found that the platinum resistance thermometer when carefully calibrated, using the boiling point of sulphur and the boiling and freezing points of water, could be used at temperatures as high as 1000°C. with small error by extrapolating with the formula developed at the lower temperatures.

Henning³ has shown, however, that the parabolic formula does not apply for platinum below -40° C.

Palladium may be used for temperatures as high as 600°C. with the parabolic formula, but above this a fourth-degree equation is necessary to represent its behavior.

¹*Phil. Trans. Roy. Soc.*, vol. 178, p. 161, 1887.

²*Phil. Trans. Ap.* p. 119, 1892.

³*Ann. Physik.*, vol. 40, p. 635.

Nickel in the ordinary temperature range may be treated by the Callendar formula, but A and B assume reversed sign and δ is larger in magnitude.

TABLE IV

PLATINUM TEMPERATURE, DEGREES CENTIGRADE	TEMPERATURE BY NORMAL THERMOMETER, DEGREES CENTIGRADE
-200	-191
-100	- 97
0	0
+100	+100
200	203.1
300	309.8
400	420.2
500	534.9
600	654.4
700	779.4
800	910.7
900	1049.4
1000	1197.0
1100	1355.0
1200	1526.7
1300	1716.0

Resistance-thermometer Construction.—The requirements of a satisfactory resistance thermometer are: first, that the resistance at any particular temperature be a constant value, unchanging with time; second, that the bulb is able to assume quickly the temperature of its surroundings; and, third, that the protecting tube in which it is placed be able to withstand the shocks both mechanical and thermal to which the thermometer is subjected. The effect of even small traces of an impurity in a pure metal is to increase greatly its electrical resistivity. In the case of platinum at $-200^{\circ}\text{C}.$, the presence of 10 per cent of rhodium was found by Dewar and Fleming to change the resistivity by a factor of 400 per cent. So great is this change at low temperatures that a measurement of the resistivity is one of the most accurate tests for the presence of impurities. The thermometer, therefore, must be placed in protecting tubes that will keep it free from contamination throughout the temperature range in which it is used. As generally constructed, the resistance of the thermometer at $0^{\circ}\text{C}.$ is

from 10 to 20 ohms. Since the resistivity of platinum is about 0.00001 ohm-centimeters, it is necessary to use a considerable length of fine wire to obtain this resistance. The wire must not, however, be so fine that it is too fragile to work with. The details of winding this wire in such a way that no mechanical strains are introduced by the large temperature changes and the accompanying expansions, have been the subject of much investigation. The wire is generally wound on a light mica form made of two rectangular pieces of mica intersecting at right angles at their centers along the long dimension. The edges of the mica sheets are notched to hold the wire. The several leads are insulated with perforated mica washers. The platinum leads terminate in the head of the thermometer and are fused to stranded copper leads carefully adjusted to equality, which connect the thermometer to the measuring apparatus. Care should be taken to avoid the possibility of any unbalanced thermal e.m.f. Mica appears to be very suitable for the forms of these coils. At high temperatures it becomes dehydrated and flaky but is still satisfactory. The wire is annealed at about 1000°C. by passing an electric current through it both before and after winding. Dickinson and Mueller¹ have described a thermometer having a very small thermal capacity and time lag in operation. The winding form was in this case a flat rectangular sheet and the case was a flattened metal cylinder insulated from the platinum coil by very thin mica sheets.

Resistance Measurement by Wheatstone Bridge.—Some form of Wheatstone bridge is generally used to measure the resistance of the thermometer. As the thermal capacity of the thermometer bulb is small, the measuring current through the bulb must be kept small to avoid heating from that source. This may be accomplished by the use of a small e.m.f. on the bridge or by having a high series resistance in that arm of the bridge containing the resistance thermometer. For reasons given below in connection

¹*Bull.* 9, U. S. Bureau of Standards, p. 483, 1913; *Sci. Paper* 200, U. S. Bureau of Standards, 1913.

with compensating leads, 1:1 ratio is generally maintained between the resistances of the parallel branches of the battery circuit. A typical bridge set-up is shown in Fig. 32 in which r_4 , B and G denote the resistance thermometer, battery, and galvanometer, respectively. The resistances r_1 and r_2 are made equal at some value such as 1,000 ohms. The bridge is balanced by changing r_3 until the galvanometer shows no deflection. Since the value of r_3 , only a few ohms, is then equal to the resistance of the thermometer r_4 , it is important that the adjustment of r_3 be made without introducing any variable contact resistance. Unless the bridge is specially constructed for this purpose, the smallest division of the resistance r_3 may be 1 ohm. In using, therefore, a 1:1 ratio to obtain more precise resistance values, r_3 may be shunted by a resistance of several hundred ohms

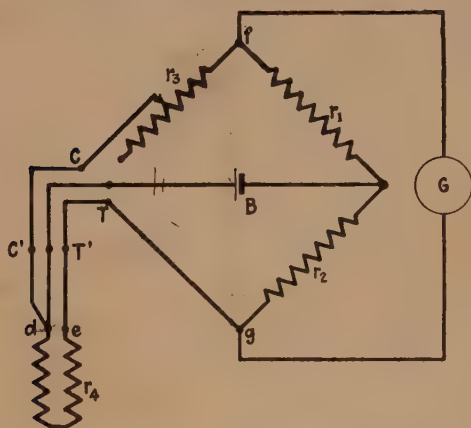


FIG. 32.—Resistance thermometer with Wheatstone bridge. Siemens three-lead compensation.

value above that of r_4 , a small variation in R allows the true resistance of r_4 to be calculated to the nearest 0.01 or 0.001 ohm.

Many special types of Wheatstone or Kelvin bridges have been made especially for resistance-thermometer work in which it is possible to read directly to 0.001 or 0.0001 ohm with no series contact resistance introduced.

Compensation for Connecting Wires. 1. *Siemen's Three-wire Method.*—The resistance bulb is commonly used at a considerable distance away from the bridge and the connecting wires which may be of different material are subjected to varying temperatures along their length. To compensate for the introduction of this uncertain resistance, various compensating devices have been

employed. In the three-wire compensation method, shown in Fig. 32, the thermometer has three identical lead wires coming from it. Two of these are attached at one end of the platinum coil and one at the other. Thus, by connecting the free end of one of the wires of the pair to the battery, it is evident that one of the lead wires is thrown in series with r_3 and only one is in series with T . By using a 1:1 bridge ratio, therefore, any resistance variation in the leads produces no error.

2. *Dummy Pair—Four-wire Method.*—Another method of compensation sometimes employed is to have, in addition to the two wires attached to the ends of the platinum coil, another pair of identical wires fastened together at their distant ends and lying side by side with but not in electrical contact with the leads from the platinum coil. The extra dummy pair is connected in series with R , so that with a 1:1

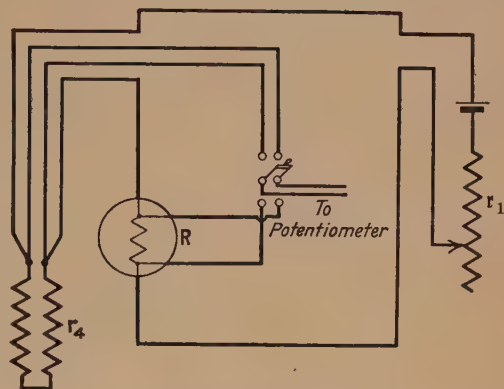


FIG. 33.—Resistance thermometer with potentiometer.

bridge ratio no error is introduced by the varying resistance in the connecting wires. The effect of the varying resistance of the lead wire is, of course, greater where the resistance of the coil is low. For this reason, if no compensating arrangement is used, the resistance of the coil should be as large as practicable.

3. *Four-wire Compensation—Unequal Lead-wire Resistance.*—It may often happen that the lead wires do not all have the same resistance. To compensate in this case it is necessary that two wires come from each end of the platinum coil as in the thermometer shown in Fig. 33. If these leads be numbered a and b from one end and c and d from the other, the thermometer may be connected to a bridge as shown in Fig. 32, where a is the wire dc' , c is

T' , and b is dc , so that lead d will not in the first case be connected to anything. When balanced

$$r_4 + c = r_3 + a.$$

Now interchange a and c and b and d and adjust r_3 to its new value r_3' if necessary, giving

$$r_3' + c = r_4 + a.$$

Hence, it will follow that

$$r_4 = \frac{r_3 + r_3'}{2},$$

and the value of the resistance r_4 is found independent of the resistance of the leads. The interchange of terminals may be accomplished by a double-throw switch.

Resistance Measurement by Potentiometer.—By connecting the resistance thermometer in series with a standard resistance, it is possible to express its resistance in terms of the standard. The resistance ratio will be the ratio of the falls in potential across the two conductors when carrying the same current. The resistance thermometer is then constructed with two connecting wires from each end, one of each pair being a potential lead. If the e.m.f. is now measured by a potentiometer, the variation of the resistance of the connecting wires can produce no effect. This method is frequently used to measure small changes in the temperature of a bath where the heating effect due to the measuring current is negligible. Figure 33 shows a wiring diagram of an arrangement of this sort.

Range and Accuracy of the Resistance Thermometer.—Resistance-temperature measurements upon pure platinum between 0 and 100°C. indicate an absolute zero on the platinum scale of about -269°C. When impurities are present, the apparent absolute zero goes toward lower temperature values. While the melting point of platinum is 1755°C., resistance thermometers have rarely been used above 1200°C. At this temperature, great care must be taken to keep the platinum free from impurities.

A coil whose resistance at 0°C . is 20 ohms has a resistance of about 27.7 ohms at 100°C . If the resistance measurement, therefore, could be made to the 0.01 ohm, a temperature variation of 0.13°C . could be observed. Considering the fact that this accuracy is obtainable over such a wide temperature range, combined with the fact that it may readily be made a recording instrument, the value of the resistance thermometer is apparent.

Unbalanced Wheatstone Bridge.—It is possible to use the resistance thermometer with a Wheatstone bridge so that the galvanometer deflections are used to indicate the temperature of the thermometer. The deflection of the galvanometer depends upon the difference in potential between f and g (Fig. 32). This is determined by the amount that r_4 differs from r_3 and the currents through the branches of the bridge. By inserting a definite fixed resistance in place of r_4 , the current may be adjusted to a standard value by varying a resistance in series with B until the galvanometer deflection is a certain definite value. Having been set to the proper current value, the resistance thermometer may be replaced in the circuit and the galvanometer scale calibrated directly in terms of temperature. It is possible to have two or more temperature scales on the galvanometer scale. One of the arms of the bridge is then so arranged that its resistance may be changed to two or more values. If two scales are provided, a typical way of arranging them might be that of having one give values from 0 to 500°C . and another give values from 400 to 900°C . This method is thus free from the necessity of constantly balancing the bridge as long as the steady current remains unchanged and, since the difference of potential between f and g is proportional to the temperature of the thermometer bulb, it may be used in connection with any indicating, recording, or controlling device in the same way as a thermocouple.

The Bolometer.—In 1881, Langley¹ developed a form of resistance thermometer of very great sensitivity and made in such a

¹ *Am. Jour. Sci.*, vol. 21, p. 187, 1881.

form that it could be used to obtain the energy distribution in the spectrum of a hot source. This device, as modified by Lummer and Kurlbaum in 1892, in measuring the total radiation from a heated body was constructed as follows: A system of strips, joined end to end so that they made a continuous electric conductor, was stamped out of a very thin metallic foil. This grating made use of one-half of the foil sheet. Another similar grating was placed over the first but electrically insulated from it in such a way that the open space in the first grating was occupied by the closed space in the second. One of these gratings was placed in the arm r_4 (Fig. 32) while the other took the place of r_1 . This system, when exposed to radiation was warmed with an accompanying rise in resistance so that, if the bridge were balanced, it would become unbalanced from the cumulative effects of both gratings. The arms r_2 and r_3 were similar gratings not exposed to the radiation to be measured and, hence, were of constant resistance. By this means a change in temperature as small as 0.0001° could be measured, and from the extreme thinness of the foil, the thermal capacity of the receiver was very small so that equilibrium was quickly established.

EXPERIMENT 1

OBJECT: To obtain a resistance-temperature curve for a platinum or nickel thermometer, using fixed known temperatures; to obtain the equation of the curve; to find δ in the Callendar correction formula.

Connect the resistance thermometer to a Wheatstone bridge in such a way that the resistance of the connecting wires is compensated. Measure the resistance of the bulb when immersed in melting ice, when above water boiling in an enclosed container under standard pressure conditions, and when similarly placed with respect to boiling sulphur or naphthalene. From the results obtained solve for α_0 , α , and β . What is the value of δ to be used in the Callendar correction formula for this thermometer? Measure the room temperature with the resistance thermometer. Explain any difference obtained between this reading and that of a good mercury thermometer.

Problems

1. A certain resistance bulb is found to have resistances of 9.0, 12.49, and 23.68 ohms, when placed in melting ice, boiling water and boiling sulphur ($444.3^{\circ}\text{C}.$), respectively. Find the equation of the resistance-temperature relation. Find the value of the δ in Callendar's correction formula.

2. At what temperature would the resistance of the above thermometer be zero if the same equation held at low temperatures? Is this the case?

3. If the resistance of each arm of the bridge shown in Fig. 32 is equal to 20 ohms when the temperature of the platinum thermometer r_4 is $0^{\circ}\text{C}.$ and a potential difference of 0.5 volt is applied by B at the ends of the parallel paths, what difference in potential would be produced between f and g , if the temperature of r_4 is raised to $200^{\circ}\text{C}.$? What should be the current sensitivity of the instrument if its resistance is 1,000 ohms in order to detect a change in temperature of $0.1^{\circ}\text{C}.$?

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CHAPTER V

OPTICAL PYROMETERS

Temperature and Color.—Skilled workmen, in treating metals, long ago recognized the fact that the tint of metals changed as they were heated. By being able to judge this tint accurately and to apply their experience, they were able to heat metals to the proper desired condition of temperature with no additional temperature-measuring apparatus. Although individuals vary somewhat in their judgment of color, the following table approximates a relationship between tint and temperature:

TABLE V

Tint	Temperature, degrees Centigrade	Temperature, degrees Fahrenheit
Lowest visible red.....	470	878
Dull red.....	600	1112
Cherry red.....	700	1292
Light red.....	850	1562
Yellow.....	1000	1832
White.....	1150	2102

The color ascribed to a body is due to the wave-length or combination of wave-lengths in the radiations coming from it to the eye. To be visible some radiation must be present whose wave-length is shorter than 0.00008 centimeter or 0.8 micron which is the longest wave-length capable of affecting the organs of vision. As the temperature of the radiating body is increased, the radiation is found to include shorter and shorter wave-lengths. The shortest wave-length capable of affecting the eye is about 0.00003 centimeter or 0.3 micron, which gives the sensation of a violet color. While bodies at very high temperature emit radiations of this wave-length, they also emit all other longer

wave-lengths so that the total result is the sensation of a white or a bluish-white color.

Black-body Conditions.—Although it is evident that the radiations from a body increase with temperature, it may also be shown that the radiations from all bodies are not the same at a given temperature. For instance, if carbon and polished platinum are both heated to such a temperature that the carbon becomes incandescent, it will be noted that the platinum is emitting much less light than the carbon, even though the temperature of the two bodies is the same. Further investigations would show that all substances have different energy-emitting power or emissivity at the same temperature. It would appear, therefore, that the measurement of temperature by variations in energy radiation is impossible. Kirchhoff's conception of a "black body" has removed the difficulty and at present all optical and radiation pyrometers are calibrated in terms of black-body conditions.

Since all bodies exhibit different emissivities, it is possible to conceive of a body which has maximum emissivity. Such a body is called a black body and its emissivity is assigned as 1. The emissivities of all other bodies are therefore fractions of the emissivity of a black body. Kirchhoff¹ defined a black body as one which absorbs all radiations falling upon it and reflects and transmits none. The radiations from such a body would, therefore, be due to temperature only. All other bodies absorb part of the radiations falling upon them and reflect or transmit the rest. Their radiations are not due, therefore, to temperature alone.

The laws of radiation which will be discussed in subsequent sections are all stated in terms of black body radiations. While it might seem that the black-body conception would necessitate large corrections in temperature measurements by optical and radiation pyrometers, it is a fact that a good many commercial operations requiring high temperatures are carried out under conditions which approach very closely those of the black body.

¹ *Pogg. Ann.*, vol. 109, p. 275, 1860; *Ann. chim. phys.*, vol. 59, p. 124, 1860.

Also, the emissivities of a good many substances are very close to the emissivity of the black body.

The black body is experimentally produced by uniformly heating the walls of a hollow opaque enclosure and noting the radiations through a small aperture. The radiations thus produced are due to temperature alone and are not affected by light from other sources.

Stefan-Boltzmann Law.—Newton formulated a “law of cooling” which asserted that the rate of radiation was proportional to the

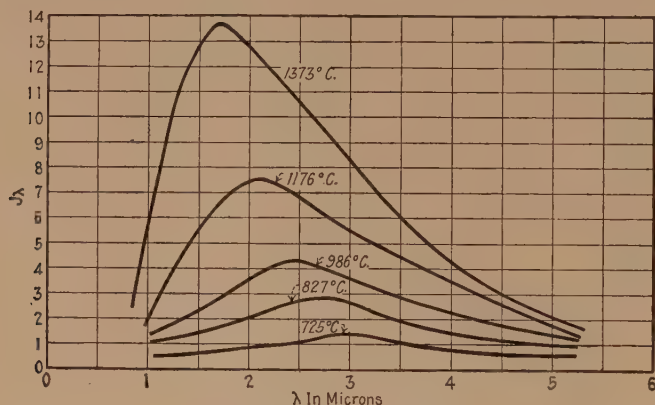


FIG. 34.—Energy distribution of black body radiator.

temperature difference between the body and its surroundings. While this law is still used when the temperature difference between the body and its surroundings is small, it was long ago recognized that it was inadequate when the temperature difference was large. An investigation to determine more accurately the relation between the total radiant energy per square centimeter per second and the temperature of the body was carried out by Tyndall.¹ In this experiment, the radiating body was the opening of a heated hollow enclosure. Thus it gave black-body radiation. From results obtained by Tyndall, and other considerations, Stefan² concluded that for a black body radiator the energy emitted per square

¹ *Phil. Mag.*, vol. 28, p. 329, 1864.

² *Wien. Ber.*, vol. 79, B. 2, p. 391, 1879.

centimeter per second was proportional to the fourth power of the absolute temperature of the radiating body. This quantity is represented in Fig. 34 by the total areas under the curves. If the body, however, were placed in an environment at some other temperature, it must also be receiving heat proportional to the fourth power of this temperature, so that the net loss in energy per square centimeter per second is given by the following expression:

$$W = \sigma(T_1^4 - T_2^4).$$

σ is a universal radiation constant whose value appears to be 5.709×10^{-12} when W is expressed in joules, and T_1 and T_2 are the absolute temperatures of the radiating body and its surroundings, respectively.

Boltzmann¹ in 1884, from thermodynamic reasoning, deduced the same result theoretically. This equation has since been experimentally verified by many observers for temperatures as high as 1550°C., using the gas thermometer to measure the temperatures. Having established the validity of such a relationship for temperatures up to 1550°C., then if some device were at hand for comparing the received energies at higher temperatures, an extrapolation of the law would enable the higher temperatures to be evaluated. Devices for comparing the total radiant energies from bodies are called "total radiation pyrometers" and will be discussed in the next chapter.

Wien's Law.—An experiment, whose object was to determine the intensity distribution of the radiation from a uniformly heated enclosure in terms of the wave-length of the radiation and the temperature of the enclosure was carried out by Lummer and Pringsheim.² The experiment was later repeated by these observers and others. The enclosure in the original experiment was a hollow carbon cylinder electrically heated. Its temperature was measured by a thermoelement calibrated in terms of the standard nitrogen thermometer. The radiation was allowed to

¹ *Wied. Ann.*, vol. 26, p. 287, 1884.

² *Wied. Ann.*, vol. 63, 395, 1897.

pass out through a narrow opening and to be dispersed by a fluorite prism. A bolometer was used to obtain the energy distribution of the spectrum. The results obtained are pictured in Fig. 34. The ordinate J_λ is a quantity such that $J_\lambda d\lambda$ represents the energy per cm.² per second carried by wave-lengths whose values lie between the limits λ and $\lambda + d\lambda$. Thus, areas on the figure represent energies. It is observed that as the temperature is increased, the intensity of each wave-length increases, but does not increase equally. From the figure, when the temperature is increased from 1250 to 1646° abs., the ordinate at 1.0μ changes by a factor of 30 while that at 1.5μ changes by a factor of 5. Thus, at higher temperatures, a larger part of the energy is carried in shorter wave-lengths, which accounts for the observed change in color.

The law connecting the radiation intensity J_λ , the wave-length λ , and the absolute temperature of the emitting enclosure was first formulated by Wien¹ in 1896, from theoretical considerations. The final form of the equation which he obtained is as follows:

$$J_\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} \quad (1)$$

where λ and T denote wave-length and absolute temperature, respectively, and c_1 is a constant depending upon the arrangement of apparatus, distance from source, etc., while c_2 might be considered a universal constant for radiation processes, and e is the base of the Napierian logarithm system. By substituting the known coordinates of any two points in Fig. 34, two equations are obtained from which it is possible to obtain values of c_1 and c_2 . If λ is expressed in microns (0.001 millimeter) and T in degrees absolute, c_2 is found to have the value 14,330. Since the original work of Lummer and Pringsheim was carried out before the accurate work of Day and Sosman² upon the high-temperature scale, the constants of the Wien law have involved considerable uncertainty.

¹ *Wied. Ann.*, vol. 58, p. 662, 1896.

² *Loc. cit.*

Planck's Law.—The Wien equation was at first thought to represent the experimental facts exactly. More accurate experimental data, however, revealed the fact that there was unquestionably a discrepancy between the experimental and theoretical laws. This was especially noticeable at large values of T and λ . In 1901, Planck,¹ starting with rather radical assumptions regarding the conditions of equilibrium and the energy distribution of the oscillators which he assumed existed in the heated enclosure, arrived at a theoretical result slightly different from that of Wien, namely,

$$J_{\lambda} = c_1 \lambda^{-5} \left(e^{\frac{c_2}{\lambda T}} - 1 \right)^{-1}. \quad (2)$$

The assumptions made in the development of this formula led to the now famous quantum theory. Many precise experiments have been made to test the validity of this equation and the conclusion seems to be that it fits the experimental facts very closely throughout the entire wave-length range for the temperatures used in the experiments, which have been from 400 to about 1500°C.

Optical Pyrometer.—Now having established a valid relationship between the intensity of radiation J_{λ} of a particular wave-length λ and the temperature of the radiating body, measurements of J_{λ} might be used to compare the temperatures of different radiating bodies provided the intensity measurements are made for the same wave-length. If a device is available for readily comparing the values of J_{λ} , it might be calibrated in terms of the gas thermometer which has been used up to 1550°C. and then by extrapolation it might be used to measure temperatures far above the range of the gas thermometer, provided the radiation law is valid for all temperature values.

Various devices have been suggested and used practically to compare values of J_{λ} in a particular wave-length region, as the temperature changes. This apparatus generally assumes the form of an optical telescope with certain auxiliary attachments

¹ *Ann. Physik.*, vol. 4, p. 553, 1901.

and is called an "optical pyrometer." In determining the scale law of these instruments, the monochromatic wave-length is generally obtained by the selective transmission of a glass plate (usually red, $\lambda = 0.63\mu$) placed in the path of the radiation at the eyepiece of the telescope. In this wave-length region, the difference between the Planck and the Wien equations is small, and therefore the simpler Wien equation will be used in the following discussion.

Disappearing-filament Optical Pyrometer. Morse Type.—Figure 35 shows an optical pyrometer, manufactured by the Leeds

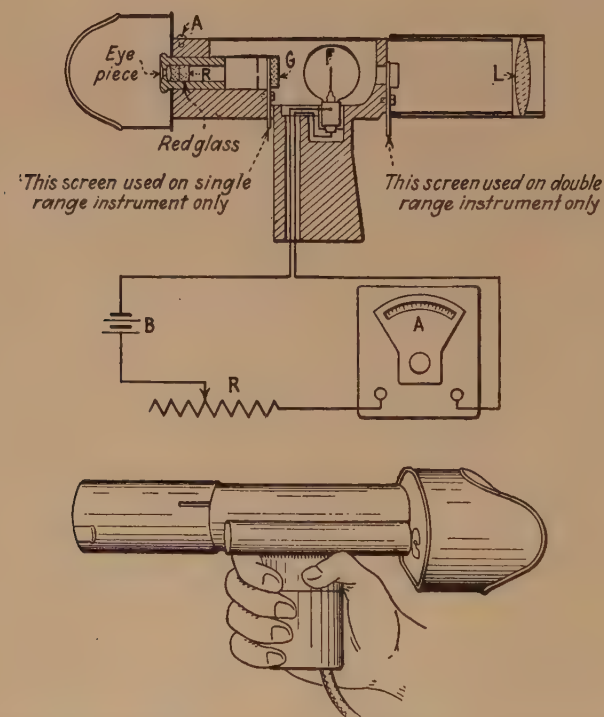


FIG. 35.—Optical pyrometer of disappearing filament type. (Leeds and Northrup Co.)

and Northrup Company. The essential parts of the apparatus are an eyepiece E ; an objective lens L ; a red glass R , which absorbs all radiations except a narrow wave-length region in the red; the filament of an electric lamp F placed in the common focal plane

of both E and L ; a milliammeter A to measure the current through the filament F ; a battery B ; and a variable resistance R .

In the earliest form of optical pyrometer suggested by Le Chatelier,¹ instead of the electric lamp L , the instrument was provided with a side arm carrying a standard flame lamp which by means of a lens and an inclined reflector produced an image in the common focal plane of E and L . An iris diaphragm was used to reduce the quantity of light entering the telescope in order to obtain an intensity match with the standard lamp. Morse² suggested the use of the electric lamp, whose current could be

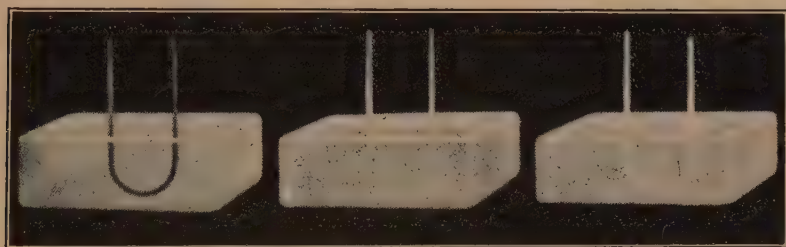


FIG. 36.—Intensity match in optical pyrometer of the disappearing filament type.

varied to obtain an intensity match with the radiation through the objective. The apparatus used by Morse, however, had no lenses and these were later introduced by Holborn and Kurlbaum,³ giving an instrument similar to that shown in Fig. 35.

In operation, the ocular is first focussed upon the lamp filament and the telescope is then pointed at and focussed upon the high-temperature source. The filament, whose temperature and hence brightness, may be varied by changing R , is superimposed upon the image of the source produced by the objective. The setting of the pyrometer then consists in adjusting R until the tip of the filament which is generally made with a downward loop, just merges in brightness with the bright background of the image of the high-temperature source, as shown in the center of Fig. 36. The reading

¹ *Compt. rend.*, vol. 114, p. 214, 1892.

² *Am. Machinist*, 1903.

³ *Ann. Physik*, vol. 10, p. 225, 1902.

of the milliammeter for this condition of intensity match is then used as an indication of the temperature of the source.

Scale Law of Morse-type Disappearing-filament Pyrometer.—The relationship which might be expected to exist between the temperature of the source and the readings of the milliammeter may be approximated as follows: When the pyrometer is properly focussed, the energy per square millimeter per second through the image formed by the objective in the plane of the filament is equal to the energy per square millimeter per second radiated by the filament normal to its surface. The former value may be expressed from Wien's law as

$$J_{\lambda} = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}, \quad (1)$$

while the latter is related to the temperature of the filament by a similar relationship, if the filament be considered as a radiating black body,

$$J_{\lambda} = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_f}}, \quad (3)$$

where T is the temperature of the source and T_f the temperature of the filament. The temperature of the filament need not be known since it is related to the energy supplied to it and radiated from it by the Stefan-Boltzmann law. The filament temperature will take such a value that the rate of receiving heat is equal to the rate at which it is lost. By neglecting the loss by thermal conduction and the gain by radiation from surrounding bodies, it therefore follows that

$$\sigma A T_f^4 = R I^2,$$

where A is the area of that part of the filament whose resistance is R . Now if the resistance of the filament be considered constant together with σ and A , it follows that

$$c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = C_1' \lambda^{-5} e^{-\frac{c_2}{(\lambda k I^{\frac{1}{2}})}}, \quad (4)$$

By taking the logarithm of each member and combining the constants, the equation may be written in the following simple form for a definite wave-length:

$$\frac{1}{T} = \frac{A}{I^{\frac{1}{2}}} + B, \quad (5)$$

where A and B are constants. Thus, a straight line should be obtained if the reciprocal of the temperature is plotted against the reciprocal of the square root of the corresponding current value. It should then be possible by knowing the current values

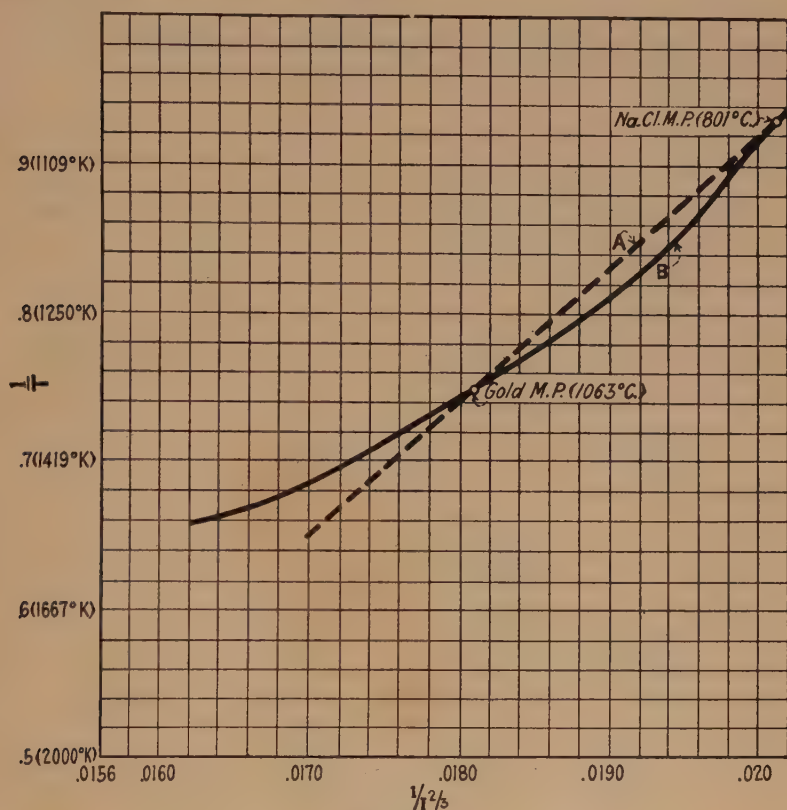


FIG. 37.—Scale law for Leeds and Northrup optical pyrometer.

for any two known temperatures to obtain a complete calibration of the instrument. Now R is probably not constant but varies directly with T for many metals. If this be assumed then the exponent of I becomes $\frac{2}{3}$ rather than $\frac{1}{2}$.

$$\frac{1}{T} = \frac{A}{I^{2/3}} + B. \quad (6)$$

In Fig. 37, A is such a curve where the known temperatures are the melting point of gold, 1063°C., and the melting point of sodium

chloride 801°C. Curve *B* shows the actual relationship between *I* and *T*. Several reasons may be given to account for the difference between the two curves actual and ideal. It may be accounted for by the fact that the assumptions made in the development involved approximations which were not quite permissible. It is practicable to express the relationship between milliammeter readings and temperature by the following empirical equation

$$I = A + BT + CT^2. \quad (7)$$

Thus, to calibrate the instrument completely, the current at three known temperatures is obtained and the constants *A*, *B*, and *C* determined.

F. and F. Optical Pyrometer.—Another disappearing filament optical pyrometer in which the intensity match is obtained in a dif-

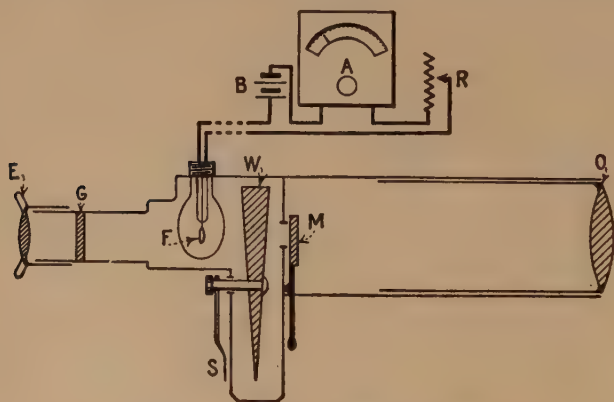


FIG. 38.—F. and F. optical pyrometer.

ferent way is shown in Fig. 38. This instrument is called an F. and F. optical pyrometer and is manufactured by the Scientific Materials Company. As before, the instrument is provided with an eyepiece, an objective, a red absorbing glass, a milliammeter, a lamp filament, and a variable resistance. In addition, a wedge of absorbing glass *W*, located between the objective and the filament, is mounted in such a way that by rotating the handle *S* the thickness of the absorbing wedge may be varied, thus altering the inten-

sity of radiation through the objective. This method of obtaining a brightness match between the source and standard lamp was first employed by Féry. Attached to S is a pointer which moves over a circular scale whose reading may be noted. In operation the filament current is first adjusted to a predetermined constant value and is maintained continuously at that value. The pyrometer is focused upon the source and intensity match obtained by turning S until the filament and background are indistinguishable. The angular reading of S may be expressed directly in temperatures. The range of the pyrometer may be changed either by moving the arm M , which puts an additional absorbing glass between the filament and the objective, or by changing the constant value of the filament current.

Absorption of Radiation.—If radiation of intensity I_0 is incident upon a thin layer of absorbing material, an amount of radiation I will emerge from the distant side of the absorbing layer. The intensity of the emergent radiation is less than that of the incident radiation by the amount absorbed and transformed into heat by the absorbing layer. The amount absorbed is proportional to the following factors: thickness of the absorbing layer, intensity of the incident radiation I_0 , and the absorbing power of the material u .

Thus, $dI = -uI dx$ where the minus sign indicates that the radiation decreases as the thickness dx increases. For a layer of finite thickness t , the above equation is integrated between the limits 0 and t for the thickness and the corresponding limits for the radiation I_0 and I .

$$\frac{dI}{I} = -u dx \quad (8)$$

from which

$$I = I_0 e^{-ut}.$$

u is termed the coefficient of absorption and is numerically equal to the reciprocal of that thickness of material that would reduce the emergent I to $\frac{1}{2.718}$ of the incident radiation intensity I_0 . This

same equation applies equally well in other branches of physics where absorbing media are encountered such as x -rays, sound, etc. when the appropriate absorption coefficient is used.

Scale Law of the F. and F. Optical Pyrometer.—The energy which is radiated by the filament per unit area per second is constant if the filament current is kept constant. When an intensity match

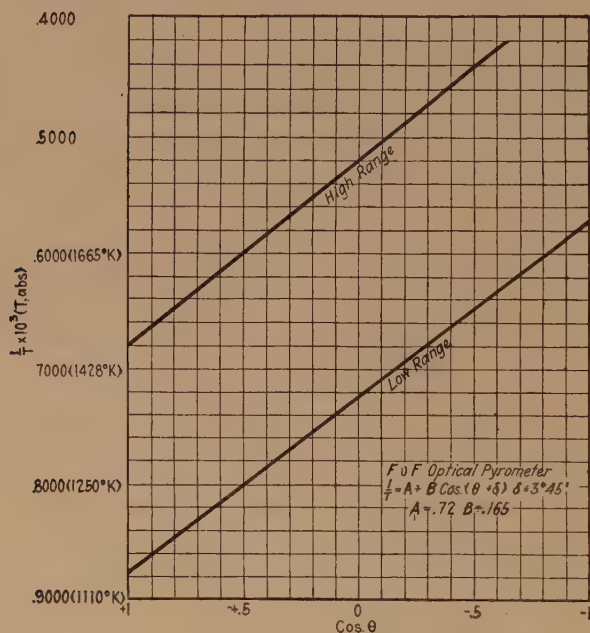


FIG. 39.—Calibration of an F. and F. optical pyrometer.

is obtained in adjusting this pyrometer, the energy radiated per square millimeter per second by the filament must equal that of the background of the filament which comes through the objective and the absorbing wedge. Due to absorption in the absorbing wedge, only the fraction $\frac{I}{I_0}$ of the radiation that would be expected by the Wien law is present. Thus,

$$J_\lambda(\text{filament}) = \frac{I}{I_0} c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = e^{-ut} c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = k \quad (9)$$

from which it follows by taking the logarithm of each side and grouping constants for a definite wave-length that

$$\frac{1}{T} = A't + B'. \quad (10)$$

A' and B' are constants. Now from the geometry of the hemicircular wedge, the thickness t for any angular setting θ equals the maximum thickness t_0 times the quantity $\frac{(r - r \cos \theta)}{2r}$. Substituting this value in Eq. (10) gives

$$\frac{1}{T} = A \cos \theta + B. \quad (11)$$

A and B are constants whose value may be determined by knowing the angular settings corresponding to any two known temperatures. The value of expressing the scale law in this way is evident since a complete calibration of the instrument may be obtained by using only two fixed points. Figure 39 shows the actual calibration of an F . and F . instrument using certain fixed melting points for the calibration. The lines are remarkably straight for both high and low ranges showing the validity of the above development.

Polarizing Type of Optical Pyrometer. *Wanner Optical Pyrometer.*—Figure 40 shows the detailed construction of a Wanner optical

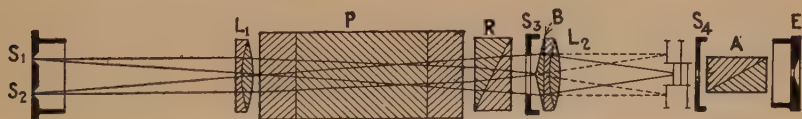


FIG. 40 — Wanner optical pyrometer.

pyrometer. This instrument makes use of polarized light and is different from the two preceding instruments in that the monochromatic radiation is obtained by a direct vision spectroscope, rather than by the use of colored glasses. The eyepiece e carries an analyzer A for polarized light. The field of view consists of two half circles separated by a common diameter. One of the half discs is illuminated by radiation coming from a semistandard electric lamp through the slit s_2 while the other half is illuminated by

radiation coming from a standard amyl-acetate lamp through the slit s_1 . The light from these two sources is polarized in passage by the Rochon prism P , each source giving two components polarized at right angles. The two perpendicularly polarized beams from each slit give rise to eight beams after passing through the biprism B . The optical system is so adjusted that all of these beams except one from each slit is lost by reflection against the walls of the telescope tube. The beams which are allowed to pass are polarized at right angles to each other. Thus, the analyzer may be set so as to allow either half circle to appear light or dark.

In operation, the pyrometer is first sighted toward a standard amyl-acetate lamp burning under specified conditions. The analyzer is set to some definite angular position and the current through the electric lamp varied by adjusting a series resistance until both halves of the circular field are of the same brightness. The filament current is now observed and this value is maintained until a future check shows that it has changed. A change will gradually occur, due to deterioration of the filament as it is operated at a rather high temperature. The amyl-acetate lamp may now be removed and the pyrometer sighted upon the high-temperature source. The analyzer is now rotated until the two half circles are of the same brightness. From the angular reading when in the position of equal brightness, the temperature may be found.

Pyrometers of this principle with slightly improved construction are now manufactured by several other makers, notably Scientific Materials Company, Pittsburgh, and Cambridge and Paul Instrument Company, England.

Scale Law of the Wanner Optical Pyrometer.—When the brightness of the two half circular fields is the same, the analyzer must be in such a position that the projections upon this direction of the two perpendicular vectors, representing respectively the amplitudes of vibration, are the same. Since the electric lamp is continually operated by the same current, its radiation intensity J_λ and, hence, also the corresponding amplitude of vibration which is

proportional to the square root of the intensity are constant. This is represented in Fig. 41 by the vertical vector.

The horizontal vector represents the amplitude of vibration of the radiation from the source of unknown temperature. This radiation may be related to the temperature of the source by the Wien law. Thus,

$$\sqrt{J_{\lambda(\text{standard lamp})}} \cos \theta = \sqrt{J'_{\lambda(\text{source})}} \sin \theta = \sqrt{c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}} \sin \theta. \quad (12)$$

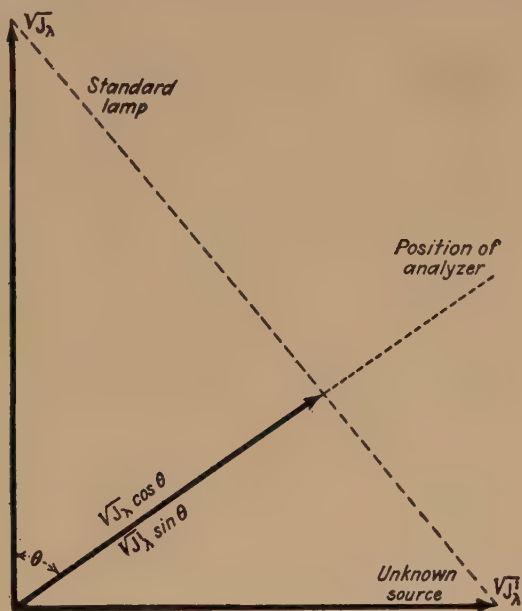


FIG. 41.—Vector diagram for Wanner pyrometer.

From this equation it follows by taking logarithms that the angular readings are related to the corresponding temperatures by the following:

$$\frac{1}{T} = A \log \tan^2 \theta + B, \quad (13)$$

where A and B are constants. Thus, if any two temperatures and their corresponding angular settings are experimentally determined, the instrument is completely calibrated, since $\frac{1}{T}$ plotted with $\log \tan^2 \theta$ gives a straight-line curve. Figure 42 shows a typical

curve of this type where the temperatures were certain standard calibration temperatures. The values lie almost in a straight line. The range of the pyrometer may be extended by the use of absorbing glasses to reduce the radiation coming through the slit s_1 , or by using a different angular setting of the analyzer during the adjustment of the proper current through the electric lamp.

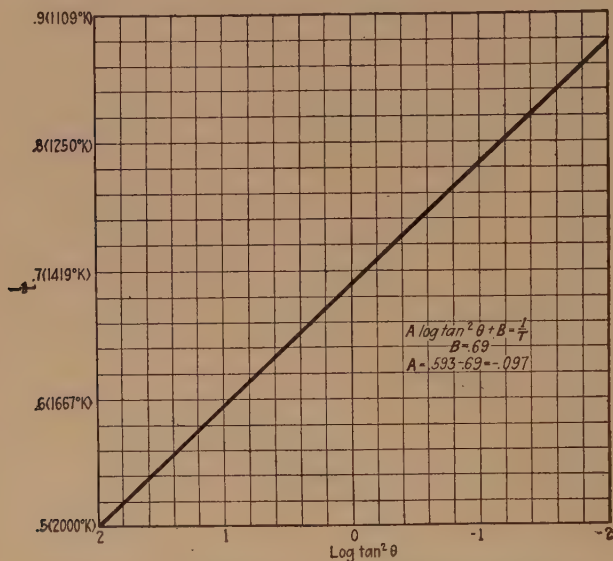


FIG. 42.—Calibration of a Wanner optical pyrometer.

Effect of Varying the Distance between Pyrometer and Source.

It might appear that a pyrometer, which reads correctly for a certain distance between the pyrometer and furnace, would be in error if the distance were altered. For an increased distance a smaller amount of energy would be received by the objective. If the pyrometer is kept properly focused, however, the size of the image produced by the objective is decreased so that the energy per square millimeter per second remains practically unchanged. This may be shown to follow from the simple lens formula

$$\frac{1}{P} + \frac{1}{Q} = \frac{1}{F}$$

where P , Q , and F denote the object distance, image distance, and focal length of the lens, respectively. Also $\frac{Q}{P}$ equals the magnification produced by the objective. Since P is always a large quantity, changes in P produce negligible changes in Q . Hence, the magnification varies inversely as P . Thus, if P is increased, the energy received by the objective varies inversely with P^2 while the area of the image formed by the objective also varies inversely as the P^2 , hence the energy per square millimeter in the image remains unchanged and the readings of the pyrometer would be independent of the distance. If it should happen, however, that the high-temperature source was being viewed through an aperture which was such that the objective was not completely covered with the radiation from the source at the shorter distance, then on moving the objective farther away, the energy received by the objective would be constant until such a distance was reached that the objective was completely covered by the radiation coming through the aperture. In this case then it would follow that the temperature would appear to increase as the distance of the pyrometer from the aperture increased.

The presence of absorbing gases between the source and objective would, of course, always make the pyrometer read too low, and this effect would increase with the thickness of the gas layer or distance.

Emissivity of Materials and Its Effect upon Optical Pyrometer Reading.—The curves, shown in Fig. 34, show the intensity distribution of the radiation from a uniformly heated enclosure, in terms of wave-length and temperature. Such a body is termed a black body and these curves are spoken of as black body curves. A black body will absorb completely all radiation incident upon it. It has been shown experimentally, however, that if a mass of metal be substituted for the uniformly heated enclosure at the same temperature, the curve obtained lies below that for the black body. In Fig. 43, along with the intensity wave-length distribution

curve for a black body at $1000^{\circ}\text{C}.$ is shown a similar curve for a mass of gold at the same temperature. It is evident that while the radiation from the gold has the appearance of a black-body curve, it lies well below that of the black body at the same temperature, particularly in the long wave-length region.

If the radiation intensity from a black-body at any temperature, in some wave-length region, be denoted by 1, then the intensity of radiation from the non-black body at the same temperature

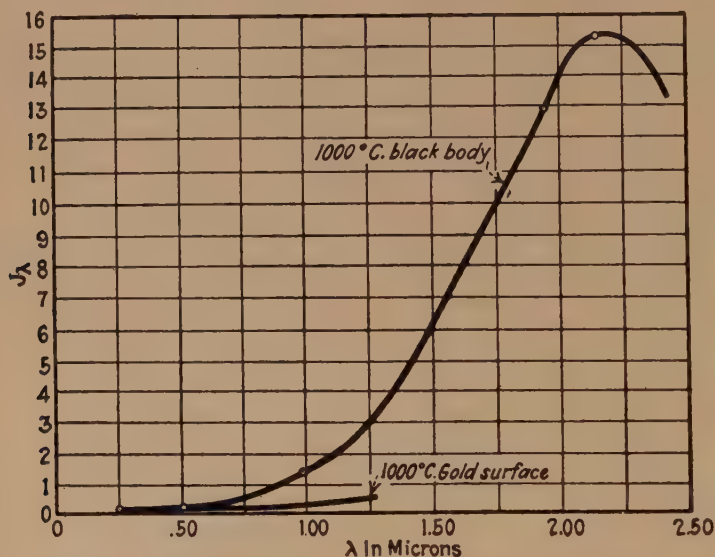


FIG. 43.—Relative radiation of a black body and a gold surface.

in the same wave-length region is less than one and the ratio of the latter quantity to the former is called the emissivity E_{λ} of the substance of which the non-black body is made, for the particular wave-length λ .

Table VI shows the emissivity of gold for a few wave-lengths at its melting point. It is thus evident that if an optical pyrometer had been calibrated in terms of a black-body source, then a non-black body would have an apparent temperature less than its true temperature since the smaller radiation intensity would allow a brightness match with a smaller filament current. If the emis-

TABLE VI.—EMISSIONITY OF GOLD AT THE MELTING POINT
(*Stubbs and Prideaux.*)

WAVE-LENGTH IN μ	EMISSIONITY
0.7014	0.184
0.6712	0.203
0.6409	0.232
0.6149	0.263
0.5895	0.304
0.5649	0.347
0.5418	0.390
0.5186	0.434
0.4961	0.473
0.4750	0.503

sivity E_λ of the substance, however, is known, then it becomes possible to calculate the true temperature from the apparent temperature. Since the actual radiation intensity from the non-black body is E_λ times the radiation that would be given by a black body at the same temperature, then from Wien's law it follows that

$$J_\lambda(\text{actual}) = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{apparent}}}} = E_\lambda c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} \quad (14)$$

where T_{app} and T represent the apparent and true temperatures, respectively.

$$\frac{1}{T} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e E_\lambda = \frac{0.63}{14,330} (2.302) \log_{10} E_\lambda = \frac{\log_{10} E_\lambda}{9,880} \quad (15)$$

Thus, if c_2 and λ are known, it is only necessary to know any pair of true and apparent temperatures to find E_λ . For any given set of conditions the right-hand member of Eq. (15) is a constant which may be evaluated as a whole by measuring any true temperature and its corresponding apparent temperature. Knowing this constant value, the true value of any apparent temperature may be found. It is apparent that the difference between the true and apparent temperatures for any value of E_λ becomes greater as the temperature increases. As an illustration, if the emissivity of a substance were 0.5, a true temperature of 1000°C. would have an apparent temperature of 948°C. while temperatures of 1500°C. and 2000°C. would appear as 1398°C. and 1826°C. Figure 44 shows a

graphical method of illustrating the relation of true and apparent temperatures for any value of emissivity. Another ingenious graphical method due to Pirani¹ is shown in Fig. 45, in which a straight line through the observed temperature shown in columns s or s' and the emissive power A will, when extended, give the true temperature from columns T' or T'' . If a pyrometer is to be used

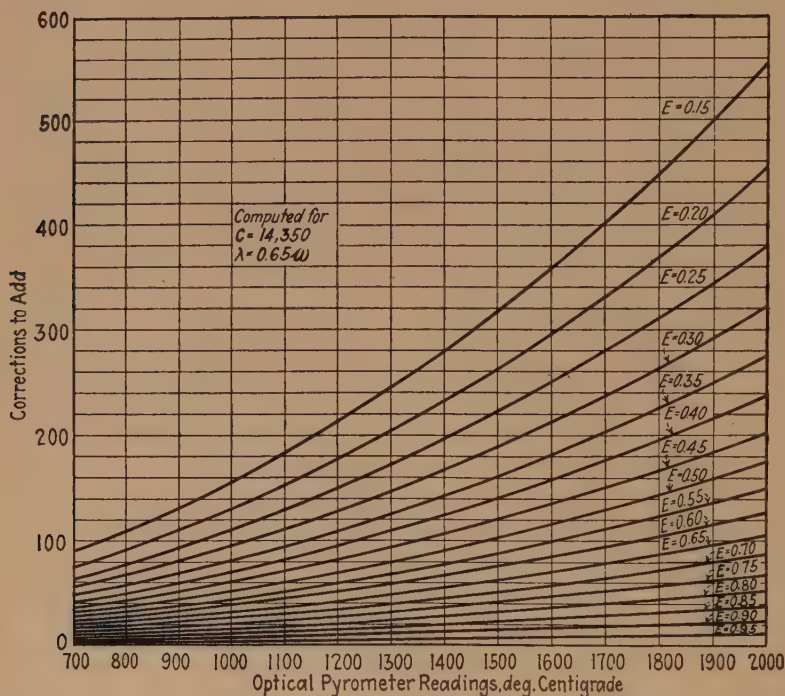


FIG. 44.—Corrections due to emissivity, in readings of optical pyrometers. (T. P. 170 U. S. Bur. Standards.)

for a single purpose where the emissivity is constant the scale may be corrected so that it gives directly the true temperature, taking into account the emissivity of the surface.

Table VII shows the emissivity of a few unoxidized metal surfaces for the wave-length 0.65μ , at temperatures close to the melting points for the first three metals.

¹ *Phys. Ges. Verh.*, vol. 12, pp. 301-1054, 1910, and vol. 13, p. 19, 1911.

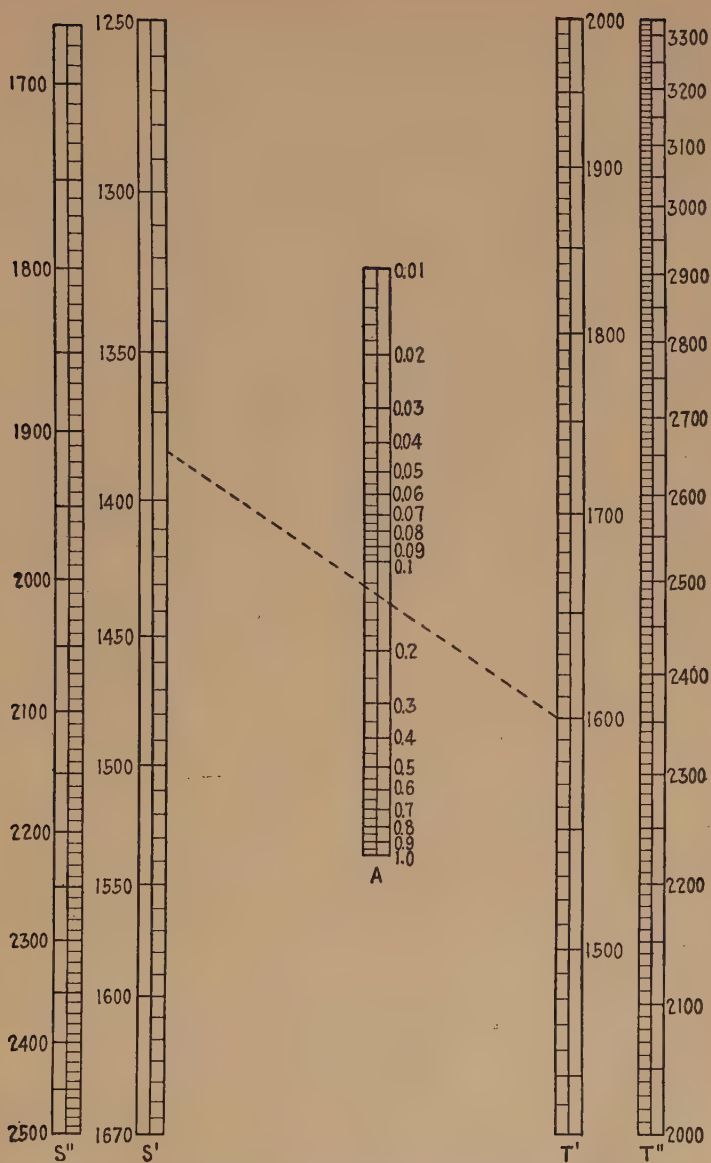


FIG. 45.—True and apparent temperatures. Pirani method.

TABLE VII.—EMISSIVITY FOR WAVE-LENGTH REGION 0.65μ

	Substance	Emissivity
Gold.....	Solid	0.13
	Liquid	0.22
Platinum.....	Solid	0.33
	Liquid	0.38
Copper.....	Solid	0.11
	Liquid	0.15
Tungsten.....	Solid	0.4
Carbon.....		0.9

The Optical Wedge.—Mendenhall¹ has shown that even for materials whose emissivity is small, black-body conditions are closely approached if the pyrometer is sighted upon the inside surface of a hollow wedge of the material having a small angular opening. Let E_λ , E_λ' , and R_λ denote, respectively, the emissivity of a black body; the emissivity of the material of a non-black body; and the reflecting power of the material of the non-black body all for some wave-length λ . Kirchhoff showed that the following relationship existed:

$$R_\lambda + E_\lambda' = E_\lambda = 1, \quad (16)$$



FIG. 46.—Radiation from a hollow wedge-shaped enclosure.

that is that a good reflector is a poor emitter and *vice versa*. Hence, in Fig. 46, the radiation coming from A to the pyrometer objective is made up of some radiation emitted by the region A, some emitted by B and reflected by the region at A, some emitted at C and reflected successively at both B and A, etc. Thus, the total emissivity of the region A is

$$E_\lambda' + R_\lambda E_\lambda' + R_\lambda^2 E_\lambda' + R_\lambda^3 E_\lambda' + \text{etc} = E_\lambda' + R_\lambda - R_\lambda^2 + R_\lambda^2 - R_\lambda^3 + R_\lambda^3 \text{ etc} - R_\lambda^n = 1 - R_\lambda^n = 1 \text{ (approximately)}. \quad (17)$$

¹ *Phys. Rev.*, vol. 33, p. 74, 1911.

For an angular opening of 10 degrees, n may be as large as 20, and R_λ^n becomes negligible so that even if E_λ' is small, the total emissivity is close to that for a black body. Hence, if metals are viewed when enclosed in a furnace or when covered with an oxide coating or a rough surface, black-body conditions are approached, and true temperatures approximately given directly.

Nichols and Howes¹ have reported certain oxides which when heated gave off radiation in the blue region of the spectrum many times greater than that from a black body at the same temperature. The radiation was however deficient in other wave-lengths. This has been explained as not pure temperature radiation but a case of luminescence excited by the presence of some activating material, as the effect exhibited fatigue in time.

The Effect of Absorbing Media upon the Reading of Optical Pyrometers.—It was previously noted on page 91 that radiation passing through any absorbing matter would be reduced in intensity. Hence, if a window or smoke screen is interposed between the pyrometer and the high-temperature source, the apparent temperature will be less than the true temperature. Since the ratio of the actual intensity I to the intensity that would be obtained with no absorber I_0 was shown to be equal to e^{-ut} , it follows that the quantity e^{-ut} plays the same rôle as emissivity in Eq. (15). Thus, the true and apparent temperatures are related as follows:

$$\frac{1}{T} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{C_2} \log_e e^{-ut} = \frac{-\lambda ut}{C_2} = \frac{0.63ut}{14,330}. \quad (18)$$

Thus, if it is necessary that the absorbing substance be present, its effect may be accounted for by knowing any pair of true and apparent temperatures, since the right-hand member of equation 18 is constant. When an absorbing glass is interposed to extend the range of an optical pyrometer, it is therefore necessary to obtain a calibration at only one point in order to evaluate the whole scale. In practice, an error is generally present, due to the fact that the radiation is not strictly monochromatic.

¹ *Jour. Optical Soc. Am.*, vol. 6, p. 42, 1922.

The Effect of Reflection upon the Reading of an Optical Pyrometer.—In an optical pyrometer, brightness match is obtained between the filament and the image formed by the objective, regardless of the history of the radiation before coming to the objective. The radiation might, therefore, come from a reflecting surface which is itself cold. The apparent temperature of the body would in this case be much greater than its true temperature. For example, a wall in sunlight might have an apparent temperature of 2000°C . Hence, care must be taken that the body whose temperature is being determined is not reflecting radiation from another bright source.

Extension of Range of Optical Pyrometers.—The working range of any optical pyrometer may readily be extended beyond that which was originally intended. This is particularly easy with certain types of pyrometers such as the Wanner or the F. and F. With the instrument first mentioned, if the analyzing eyepiece is set at a smaller angular reading than the normal while the filament current is being adjusted by comparing with the standard amyl-acetate lamp, then the normal filament current value is increased and the scale readings mean higher temperatures than normally. With the latter instrument, to extend the range, the constant filament current is maintained at a value above the normal. The filament, however, should not be made to carry an excessive current so that it deteriorates rapidly. Certain other methods of extending the range may be used with any of the pyrometers.

Absorbing Screen.—The effect of interposing an absorbing layer has been mentioned. The true temperature is greater than the apparent temperature with the absorber, and if the readings of the pyrometer are obtained in a single case with and without the absorber, any subsequent apparent temperature may be converted to true temperature, as shown by Eq. (18).

Sectorcd Disc.—Another method of extending the range of the pyrometer is to place between the pyrometer and the high-temperature source, a sectorcd disc which is rotated at a sufficiently high

speed to avoid flickering. If the ratio of the open to the total space of the disc is denoted by R , then R represents the fraction of the total radiation from the high-temperature source which is received by the objective. It, therefore, may be treated like the similar terms, emissivity in Eq. (15), and $\frac{I}{I_0}$ or $e^{-u\epsilon}$ in Eq. (18), giving:

$$\frac{I}{T} - \frac{I}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e R. \quad (18)$$

Since R is measurable, T may be found from T_{apparent} without any additional experiment, provided λ and c_2 are known. Discs of this sort may be made by having two identically sectorized discs clamped together on the same axis so that they may be shifted with respect to each other, making R any desired fraction. From the emissivity diagrams it may readily be observed that in order to make T_{apparent} small with respect to T , R must be a very small fraction.

Effective Wave-length of Absorbing Glass.—As it is impossible in practice to obtain absolutely monochromatic filter glass, it is

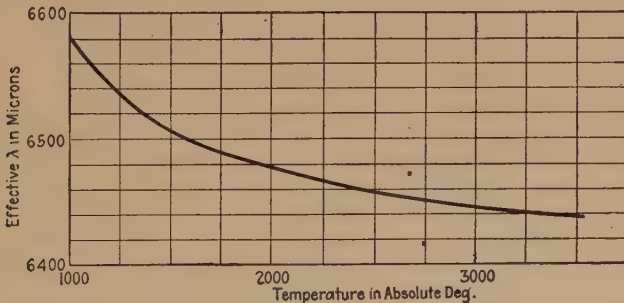


FIG. 47.—The effective transmission wave length of an absorbing glass as a function of the temperature of the source.

necessary to determine what wave-length in the spectral band transmitted is to be employed in the calculation. The quantities which are actually compared in pyrometry are the integral luminosities as observed through the filter glass. It is therefore necessary that the effective wave-lengths have the same ratio of radiation intensities throughout the temperature interval considered,

as the corresponding ratio of integral luminosities as observed through the filter glass. The ratio of the intensities of emission of the source may be measured for a number of different wave-lengths by a spectro-photometer and the corresponding ratio of integral luminosities measured by a Lummer-Brodhun photometer

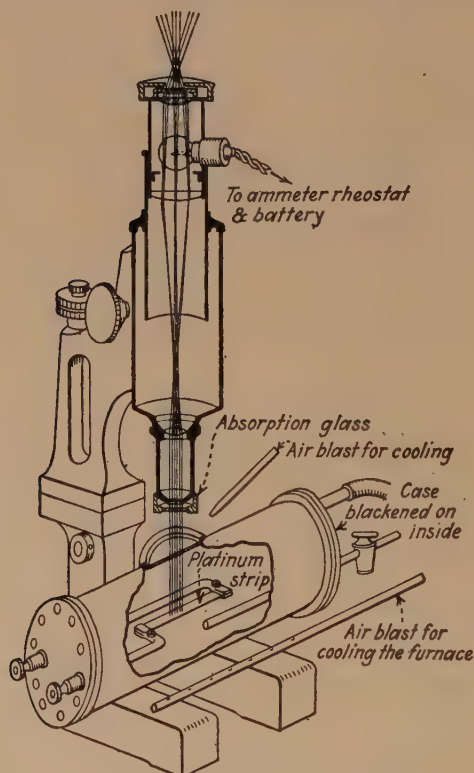


FIG. 48.—Burgess micropyrometer.

having the transmission glass over the eyepiece. In general, it has been found that the "effective" wave-length of a transmission glass shifts toward shorter wave-lengths for higher temperatures. Figure 47 shows the effective transmission wave-length obtained with a typical filter glass as the temperature is increased.

Burgess Micropyrometer.¹—In order to determine the melting points of minute samples of materials, Burgess devised an instru-

¹ "The Measurement of High Temperatures," p. 343, 1911.

ment of the disappearing-filament type employing a compound microscope instead of the usual telescope. The apparatus is shown in Fig. 48. The microscope is focused upon a platinum strip in an enclosure so that black-body conditions are approximated. A small piece of the sample under investigation is now placed upon the platinum strip which is heated by passing an electric current through it. A small lamp filament in the eyepiece is visible, superimposed upon the image of the platinum strip and by varying the current through the filament, it may be made to disappear in the field of view, as was the case in the Morse-type pyrometer. The current through the lamp filament at the instant of the melting of the "sample," which is also in the field of view, serves as an indication of the temperature. The instrument may be calibrated by using certain specimens whose melting points are known and interpolating for other values. The ordinary optical pyrometer may be used in this connection if it be sighted upon the sample and heated strip and the reading at the instant of melting observed. A microscope focussed upon the sample may be used to judge the instant of melting.

Care of Optical Pyrometers.—In those pyrometers in which the constancy of calibration depends upon the constancy of the filament of the lamp, great care should be taken to avoid excessively large currents. The lamps are normally operated much below their rated power input so that their life is much prolonged. They should be turned on only while the reading is being taken. In the Wanner instrument, comparison with the standard lamp should be made at frequent intervals. When not in use, pyrometers should be covered to avoid the accumulation of dust coverings upon the optical parts of the instruments which might produce errors in the readings. Care should be taken in focussing those instruments of variable focus, as the independence of distance follows only when the pyrometer is properly adjusted.

With the Wanner pyrometer, care should be observed not to get the instrument too warm, as some of the optical parts are set in

wax which might be softened, causing displacement of the optical parts. The Rochon prism and Nicol prism in the eyepiece are of calcite and easily scratched. The optical system of this instrument should not be disturbed as the motion of a single screw might result in very large errors in the original calibration of the instrument.

Accuracy in Optical Pyrometry.—In a progress report on optical pyrometry recently¹ published, many of the following remarks are included: optical pyrometry has grown to mean almost exclusively high-temperature measurements with the disappearing-filament type of pyrometer. This type is simple in construction, affords great accuracy and is adapted to a diversity of conditions. While the optical pyrometer may still be regarded as a secondary device, so much experimental confirmation of the quantum theory and consistent experimental values of the radiation constants have been obtained that it seems reasonable to make use of it in checking the high-temperature gas scale. The precision, accuracy, and wide range of usefulness of the disappearing-filament optical pyrometer depend on perfect disappearance of the filament with high resolving power and magnification by the eyepiece. By designing the instrument to avoid diffraction effects, Fairchild and Hoover state that it is possible to obtain a precision of $0.2^{\circ}\text{C}.$ or better at the melting point of gold. To test the consistency of the high-temperature scales in use in various research laboratories in this country and England, Forsythe recently compared the current-temperature relations for certain lamps found in these various laboratories. These high-temperature scales are based upon assumptions regarding the melting point of a metal and a value of the c_2 radiation constant. Thus the basis of the scale at the General Electric Research Laboratory and the U. S. Bureau of Standards is $c_2 = 14,350$ and the melting point of gold, $1063^{\circ}\text{C}.$ At the National Physical Laboratory, England, $c_2 = 14,350$ and the melting point of palladium, $1555^{\circ}\text{C}.$ The agreement of the

¹ *Jour. Optical Soc. Am. and Rev. Sci. Instruments*, vol. 11, p. 366.

scales was found to be very good, differences being only a few degrees over the range from 1000 to 2400°C.

EXPERIMENT 1

OBJECT: To calibrate an optical pyrometer and obtain its scale law.

Sources of Known Temperatures:

1. *Standard Broad Filament Lamps.*—It is now possible to obtain a broad filament lamp which may be calibrated so that its effective black-body temperature is expressible in terms of the current through it. Tungsten serves particularly well for the material due to its high melting point and relatively large emissivity. As lamps of this sort need not be operated near their rated power, their original calibration will change very little with time.

2. *Furnace with Thermocouple.*—A cylindrical furnace carrying at the center of the tube a plug of carbon might be used as standard high-temperature source. The temperature of the plug may be noted by a *pt. Pt-Rh*, thermocouple up to 1500°C.

3. *Fixed Melting Point.*—The melting points of various substances may be taken as known temperatures. For each of these temperatures a crucible containing the corresponding substance is placed in the furnace so that black-body conditions are approximated. The substance is now heated well above its melting point and readings of the pyrometer when focused upon the surface taken every half minute as the substance cools. A pyrometer reading time curve will now indicate the pyrometer reading at the melting point as a horizontal part of the curve.

4. *Melting Points from Electrically Heated Strips.*—Instead of using a quantity of a substance in a crucible, a strip of the material may be connected between two heavy electrodes so that a large current may be passed through it. A convenient source of supply is the secondary of a step-down transformer having a resistance in the primary for control. A slight notch should be put in the strip at one point to insure a position of maximum temperature upon which the pyrometer is focussed. The whole strip should be enclosed so that approximately black-body conditions prevail. The current is now gradually increased through the strip and the pyrometer made to follow the increase in temperature to the melting point of the strip.

The pyrometer to be calibrated may be focused (if necessary) upon any one of these high-temperature sources.

Pyrometers:

Leeds and Northrup Pyrometer.—The scale law of this instrument has been developed on page 89 as

$$\frac{1}{T} = \frac{A}{I^{1/2} \text{ or } 2/3} + B.$$

Using any two of the known temperatures, solve for A and B . Now calculate some of the other temperatures. Note the difference between calculated and true temperatures and draw curves (using $\frac{1}{T}$ and $\frac{A}{I^{1/2} \text{ or } 2/3}$ or T and I as coordinates) which show the calculated and observed values. If agreement is not good at calculated points, solve for the constants A , B , and C in the empirical equation

$$I = A + BT + CT^2.$$

Assume the temperatures known at three points. Now try other known points and observe discrepancies between calculated and observed values. Explain why the first equation may be inaccurate. If the instrument is provided with a double range, check the higher range of the instrument at one point. Can you now calculate what the other higher range readings will be if the lower range readings are known? What error is present?

F. and F. Optical Pyrometer.—Set the current through the lamp at the prescribed value and read the scale of the pyrometer for the various known temperatures. It is preferable that the scale be marked in angular degrees. Assuming two of the temperatures known, solve for A and B in the scale-law equation derived on page 92.

$$\frac{1}{T} = A \cos \theta + B.$$

Does the equation allow the temperature to be correctly calculated for other angular settings? If the scale is marked only in temperatures, the scale law could be checked by fastening on an additional circular scale. How could the zero of this scale be located? Suppose the filament current had been set at a value larger than that prescribed, what would have been the effect upon the apparent temperature?

Wanner Optical Pyrometer.—Adjust the standard amyl-acetate lamp according to directions so that the tip of the flame burns level with the top of the flame gage, and affix to pyrometer. Set the analyzing eyepiece at some particular angular setting and adjust the current through the electric lamp until the two halves of the circular field of view are of equal brightness. Note the value of the filament current and keep this constant until a re-check shows it to have changed due to deterioration of the lamp filament. The high-temperature source may now be substituted for the amyl-acetate lamp and the eyepiece rotated until brightness match is again obtained. Obtain angular settings for several known tempera-

tures. Using any two of them, solve for the constants A and B in the scale-law equation developed on page 94.

$$\frac{1}{T} = A \log \tan^2 \theta + B.$$

Do the calculated and observed temperatures agree at other angular settings? What would have been the effect of using a smaller standard angular setting in obtaining the constant current for the electric bulb? On account of stray light the pyrometer is not accurate at very small or very large angular settings. Why does the temperature increase very rapidly at large angular positions?

EXPERIMENT 2

OBJECT: To find the emissivity of various metals.

Most substances when heated to some temperature T emit less energy in every wave-length region than a black body at the same temperature. That factor which when multiplied by the intensity of the black-body radiation will give the actual radiation intensity in a particular wave-length region is called the emissivity of the substance for that wave-length E_λ .

Thus,

$$J_\lambda'(\text{non-black body}) = E_\lambda J_\lambda(\text{black body}).$$

Hence in an optical pyrometer calibrated with the Wien law as a basis of the temperature scale, the apparent temperature T_a will be too low. The actual radiation intensity may be written in terms of the true and apparent temperatures as follows:

$$J_\lambda' = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{apparent}}}} = E_\lambda c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{true}}}}$$

It thus follows by taking logarithms that

$$\frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e E_\lambda = \frac{\log_{10} E_\lambda}{9,880}, \quad (14)$$

when

$$\lambda = 0.63\mu$$

and

$$c_2 = 14,330.$$

Thus, if any pair of true and apparent temperatures are known, the emissivity of the substance may be found. It was shown on page 102 that a pyrometer when sighted upon the inside of a hollow wedge of small angular opening, gives approximately black body temperatures.

Fold a thin strip of the substance under investigation so that it makes a wedge having an angular opening of a few degrees. Connect the ends of the strip to the terminals of a step-down transformer whose primary current may be adjusted by a series resistance. Set the current through the wedge at some steady value and read the temperature both inside and outside with the optical pyrometer, as

nearly as possible at the same point. Repeat the process at another temperature. Is the emissivity of the substance a constant? What might be the effect due to the fact that the transmission glass does not give monochromatic light? Outline some other methods of obtaining the true temperatures. Only a few metals may be heated in this way without the formation of an oxide coating. What is the effect of the oxide coating and how may its formation be retarded?

EXPERIMENT 3

OBJECT: To study the effect of varying the distance of source and size of aperture upon the reading of an optical pyrometer.

In an optical pyrometer when properly adjusted, intensity match is obtained between the radiation from the source observed, and that from some standard source. In the disappearing-filament type the filament is placed in the focal plane of the objective so that the energy per unit area per second radiated from the filament and that through the image of the source are made identical. Now as the source is taken farther away, the objective receives a total amount of energy varying inversely as the square of the distance for small sources. The magnification of a lens varies how with the object distance? Hence, what is true for the energy per unit area in the focal plane of the objective?

Use as the high-temperature source any furnace or standard lamp whose temperature may be maintained constant during one set of observations. A tungsten lamp in a box having a small translucent window makes a satisfactory source. Make readings of the apparent temperatures at distances of $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, etc. meters. Interpose between the source and the objective a screen with an aperture such that the solid angle subtended by the objective is not filled with radiation at the shortest distance, and repeat the above readings. Sketch apparatus and explain results.

EXPERIMENT 4

OBJECT: The use of the sectored disc to extend the range of an optical pyrometer.

If a disc, whose ratio of open space to total space is R , be interposed between a high-temperature source and the optical pyrometer, the radiation received by the pyrometer will be reduced. Hence, that the apparent temperature of the source will be less than its true temperature would follow from Wien's Law. Thus,

$$J_{\lambda}' \text{ (with disc)} = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{apparent}}}} = R J_{\lambda} \text{ (without disc)} = R c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{true}}}}$$

$$\text{giving} \quad \frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda \log_e R}{c_2} = \frac{\log_{10} R}{9,880}$$

$$\text{for} \quad \lambda = 0.63\mu \text{ and } c_2 = 14,330. \quad (19)$$

Thus, R plays the same rôle here as emissivity on page 99 and the Figs. 44 and 45 allow the determination of the true temperature T if the apparent temperature T_{apparent} and R are known. If R is unknown, then any pair of true and apparent temperatures allow the constant value of the right-hand member to be determined and thereafter any true temperature may be found if its apparent temperature is known.

A pair of similarly slotted discs may be mounted close together on the same shaft so that they may be shifted with respect to each other giving R any fractional value smaller than one-half. The whole should be rotated at a sufficiently high speed to avoid flickering in the pyrometer. For some particular known value of R , observe the temperature of some constant source with and without the rotating disc in place. Check Eq. (19). Repeat at other temperatures. Is the value of $\frac{1}{T} - \frac{1}{T_{\text{apparent}}}$ a constant? Explain why it might be expected to change with temperature. What value of R would be necessary to observe the temperature of the sun on an optical pyrometer at 2000°C.? Try it.

EXPERIMENT 5

OBJECT: To measure the coefficient of absorption of a material and study the effect of absorbing media upon the reading of an optical pyrometer.

If radiation travels through an absorbing medium, a certain fraction of it is absorbed in the medium. As was shown on page 91 the amount transmitted I may be related to the amount incident upon the medium by the equation

$$I = I_o e^{-ut}$$

where u is termed the absorption coefficient of the material and t its thickness. Hence, an optical pyrometer sighted upon a high-temperature source through an absorbing layer will receive only $\frac{I}{I_o}$ as much radiation as it should and the apparent temperature of the source will be less than its true temperature. Hence, $\frac{I}{I_o}$ or e^{-ut} plays the same part in this connection as R in Eq. (19), and emissivity in Eq. (15), and the true temperature T is related to the apparent temperature T_{apparent} as follows:

$$\frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda \log_e e^{-ut}}{c_2} = \frac{-\lambda ut}{c_2} = \frac{ut}{22,730} \quad (18)$$

where $\lambda = 0.63\mu$ and $c_2 = 14,330$. Thus, if λ and t are known, the true temperature may be calculated from any corresponding apparent temperature. If these are not known, then any one experiment in which T and T_{apparent} are both observed suffices to evaluate the constant right-hand member of the equa-

tion and the equation may then be used to relate any observed temperature to its true value.

Sight an optical pyrometer upon some constant-temperature source and observe the temperature. Insert the subject of the investigation which may be a mica or glass window or a gas layer and observe the apparent temperature. Repeat with two and three thicknesses of the absorbing material. Does the factor t enter as indicated in Eq. (18)? Now set the temperature of the source at a higher value and repeat the observations. Express in each case the value of u obtained. Show in detail how you might extend the range of a calibrated optical pyrometer by means of an absorbing glass. How could you find the true temperature of a furnace when it is necessary to view it always through a mica window?

Problems

Optical Pyrometers

1. A Leeds and Northrup optical pyrometer requires currents of 349.3 and 456.2 milliamperes for brightness match at 800 and 1200°C., respectively. What current should be required at 1000 and 1300°C. assuming the scale law of Eq. (6),

$$\frac{I}{T} = \frac{A}{T^{\frac{1}{2} \text{ or } \frac{2}{3}}} + B.$$

The actual observed value at 1000°C. is 391 milliamperes. Then what should the value be at 1300°C. using the equation

$$I = a + bT + cT^2.$$

2. Why is the difference between the Wien and the Planck laws negligible in optical pyrometry?

3. What increase in radiation intensity should be observed at 0.4μ as the temperature changes from 1000 to 1500°C.? Also at 0.6μ ? What phenomena does this explain?

4. If in an F. and F. optical pyrometer a temperature of 1000°C. requires a setting of 41 degrees (circular measure), and 1400°C. is balanced at 72 degrees (circular measure), what position should be required for a temperature of 1200°C.? Give both the calculated and the actual positions.

5. In a calibration of a certain Wanner optical pyrometer a setting of the analyzing eyepiece at 20 is required for a temperature 990°C., while at 1255°C. the setting is 60. What angular settings should be required at 1100 and 1500°C.? Give both the calculated and the actual settings.

6. If the focal length of the objective lens on an optical pyrometer is 10 inches, what provision should be made for change of focus if the source distance varies from 1 to 30 feet?

7. A certain furnace has an apparent temperature of 1100°C . when measured by an optical pyrometer sighted upon the furnace through a glass window. If an additional window similar to the first is interposed, the apparent temperature is found to be 1060°C . What is the true temperature of the furnace?

8. What is the effective coefficient of absorption of the window material in problem 7 if each had a thickness of 2 millimeters.

9. An optical pyrometer sighted upon the inside of a hollow metal wedge reads a temperature of 1450°C ., while when focused upon the outside the apparent temperature is 1310°C . What is the emissivity of the metal?

10. The ratio of open to total space in a sectorcd disc is one-fourth. If an optical pyrometer be sighted through the rotating disc upon a furnace and an apparent temperature of 1500°C . is observed, what is the true temperature?

CHAPTER VI

TOTAL RADIATION PYROMETERS

As was evident from the discussion in the early part of Chap. V, it is possible to use either the total energy radiation from a body or the energy of one particular wave-length as a means of determining its temperature. In the present chapter those instruments using the total radiation will be discussed. The Stefan-Boltzmann law is used as the basis for calibration of total radiation pyrometers.

Féry Radiation Pyrometer.—The first device of this sort was perhaps that proposed by Féry¹ in 1902. This instrument consisted of a telescope arranged with a minute thermojunction in the focal plane of the objective. The terminals of the thermocouple were connected to a sensitive D'Arsonval galvanometer. By first adjusting the eyepiece to see the thermojunction clearly and then adjusting the objective to bring the high-temperature source into proper focus, the hot junction of the thermocouple is automatically brought into correct position. The deflections of the instrument are then proportional to the e.m.fs. of the couple which are in turn proportional to the difference between the temperatures of the hot and cold junctions of the thermocouple which by Newton's law and the Stefan-Boltzmann law is proportional to the fourth power of the absolute temperature of the radiation source.

An objection to an instrument of this sort arises from the fact that the objective lens, if made of glass, absorbs a large part of the radiation incident upon it, especially in the infra-red spectral region. Since most of the radiant energy from bodies at temperatures not exceedingly high lies in the infra-red region, the sensitivity of the apparatus is greatly reduced. Further, the fourth-power law or any other simple expression does not apply to the

¹ *Compt. rend.*, vol. 134, p. 997, 1902.

radiation transmitted by the glass lenses. Fluorite (calcium fluoride) has a remarkably small and almost constant absorption coefficient for all wave-lengths up to 10μ , and would be a suitable material from which to make the lenses of the instrument. Its use, however, is limited by its expense.

To overcome this objection, Féry¹ in 1904 suggested the use of a concave mirror similar to the astronomical reflector to replace the lenses. The final complete apparatus as now used in practice

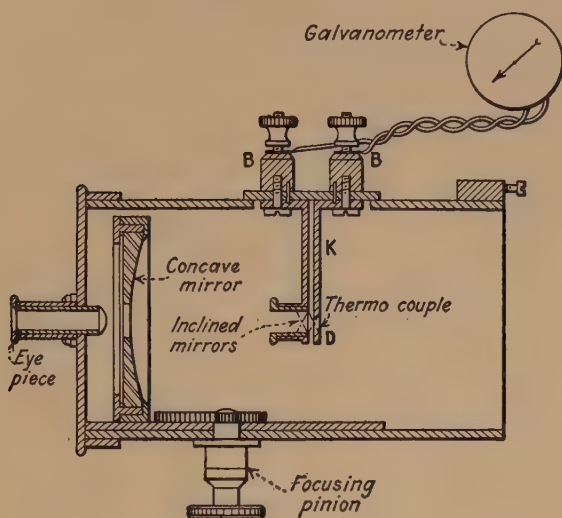


FIG. 49.—Féry total radiation pyrometer.

is shown in Fig. 49. The radiation is focussed upon the hot junction of a thermocouple whose terminals are connected to the galvanometer or millivoltmeter. The cold junction of the thermocouple is shielded from the direct radiation by suitable screens. By means of a rack and pinion screw the relative position of the hot junction and concave mirror may be changed so as to bring the junction to the focus of the mirror. In order to secure correct focus a small lens is employed in conjunction with two inclined mirrors. The effect of these mirrors is to give a circular image of the source when in correct position. If not properly focussed, the

¹ *Jour. Phys.*, September, 1904.

field of view appears as two half circles displaced with respect to each other. Without this arrangement, correct focus would be taken as that position giving a maximum reading of the galvanometer. The area of the opening at the end of the pyrometer tube may be altered by a shutter to certain fixed positions giving as many temperature ranges for the instrument.

The image formed by the objective should be larger than the area of the thermojunction so that the latter is always completely covered with radiation. If this condition is satisfied, the reading of the pyrometer should be independent of the distance between pyrometer and source since, as the distance increases, the decreased amount of energy received is accompanied by a correspondingly decreased image size so that the energy per unit area in the image is a constant. In practice, however, Burgess and Foote¹ have found that varying the distance does produce a very noticeable effect upon the pyrometer reading. An increase in the size of the image, up to five or six times that of the thermojunction area, was accompanied by an apparent increase in the temperature of the source. This effect was explained as due to the added heating of the mirror and other parts at the shorter distances, with accompanying radiation from them as radiating sources. There is also the additional effect due to the absorption of the radiation in the air and other gases through which it passes, which would be greater at the larger distances.

The cold junction of the thermocouple is shielded from the direct radiation and any general temperature changes such as that of the room would change the temperature of both junctions so that the differential effect would remain unchanged, provided the temperature-e.m.f. curve of the thermocouple is a straight line.

Care must be observed that the efficiency of reflection of the mirror is not reduced by the accumulation of dust or other surface coatings. To avoid this, the pyrometer tube should be kept closed except when actually in use, and the mirrors should be cleaned at

¹ U. S. Bur. Standards, Sci. Paper 250,

intervals, following the directions accompanying the instrument. The e.m.f. measuring instrument should have as large a resistance as possible and still be compatible in ruggedness.

Scale Law of Féry Radiation Pyrometer.—If it be assumed that the thermocouple of the instrument has a linear relationship between e.m.f. and the temperature difference between hot and cold junctions and that the deflections are proportional to the

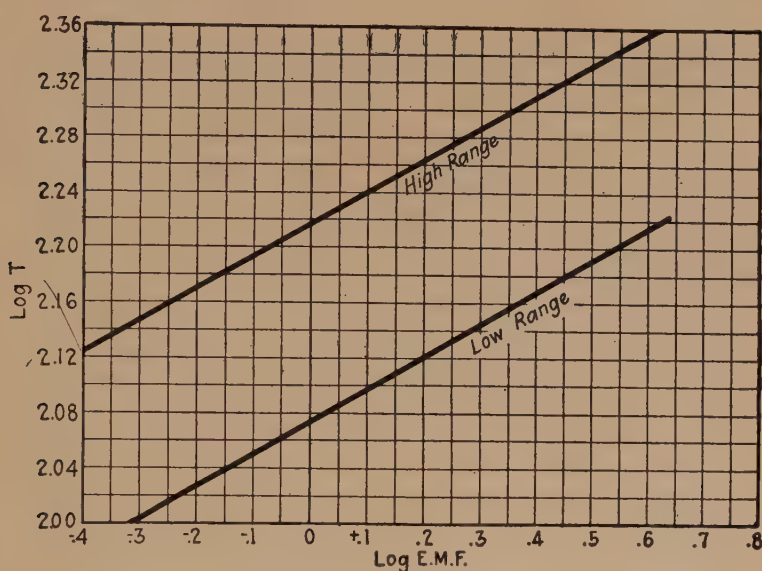


FIG. 50.—Calibration of a Féry total radiation pyrometer.

e.m.f., then the deflections are proportional to the excess temperature of the hot junction over its surroundings. By Newton's law of cooling, however, this temperature excess is proportional to the rate at which it is radiating heat which is equal to the rate at which it is receiving heat from the high-temperature source. This rate, however, is by the Stefan-Boltzmann law proportional to the fourth power of the absolute temperature of the radiating body. These relations may be summarized as follows:

$$\text{Deflection} = a (\text{e.m.f.}) = b(t_2 - t_1) =$$

$$c(T_2^4 - t_1^4) = AT^4 + B, \quad (1)$$

where a , b , c , A and B are constant. Hence, if the above approximations are not in error, a complete calibration of the instrument could be obtained by knowing only two temperatures and the corresponding pyrometer readings. These would suffice for a solution of A and B , and any other deflection could be evaluated in terms of temperature. A convenient way to represent the calibration would be to plot $\log$ (deflection) with $\log T$. This should give a straight line whose slope is 4. The actual values of $\log$ (e.m.f.) plotted with $\log T$ as obtained with a typical instrument with two ranges is shown in Fig. 50. It is observed that the slope of the lines is practically constant and the average value for $\log \frac{E}{\log T}$ is about 4.25. This value, greater than 4, may be due either to radiation emitted from heated parts of the pyrometer at the higher temperatures, or to selective absorption so that the fourth-power law does not apply exactly.

Féry Metal Spiral Radiation Pyrometer.—A modified form of the Féry¹ pyrometer made use of a small spiral coil of metal to replace the thermocouple. The spiral was made of a very light bimetallic strip consisting of two metals having a large difference in their coefficients of expansion. The advantage of this instrument lay in the fact that no troublesome galvanometer was necessary, and a pointer affixed to the end of the spiral coil could be made to move over a scale marked directly in temperature. It had the disadvantage, however, of lacking the sensitivity of the thermocouple instrument. Further, the expansion of a metal body depends upon its previous treatment; that is, it shows a hysteresis effect and consequently the readings of the pyrometer when sighted upon a definite source might be different if the pyrometer has received different treatment previous to making the observations. A general heating of the instrument would cause a shift in the zero reading of the pointer unlike the effect for the thermocouple instrument.

¹ *Compt. rend.*, vol. 134, p. 977, 1902.

Fixed-focus Radiation Pyrometers. 1. *Foster Pyrometer.*—A radiation pyrometer in which it was not necessary to focus the mirror in taking observations was proposed by Foster.¹ This arrangement is shown in Fig. 51. The thermocouple T and the opening of the pyrometer tube AB are placed at the conjugate foci of the concave spherical mirror M . It is evident that if the size of the source is such that it completely fills the base of the cone $A'B'$, $A''B''$, etc., whose apex is at O , then the energy received at O is constant, regardless of the distance of the source except for the increased absorption of the air at the greater distance. Regions

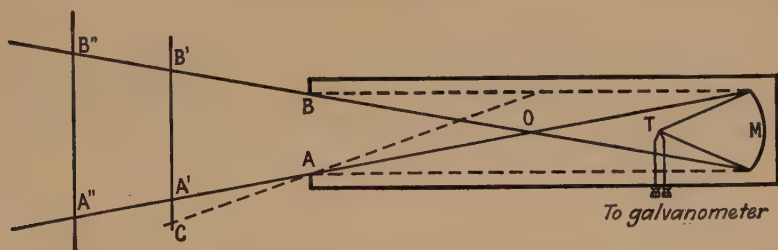


FIG. 51.—Diagram of Foster fixed focus radiation pyrometer.

on the source outside of $A'B'$, etc. can contribute no energy to O , although some energy will enter AB and be absorbed by the blackened walls of the pyrometer tube. Since the energy passing through O is focussed upon the thermocouple T , the readings of the pyrometer should be approximately independent of distance. To satisfy this condition, it must evidently follow that the diameter of the source be at least a certain fraction (usually one-eighth) of the distance between the source and the point O , whose position is generally marked by a wing nut on the side of the pyrometer tube. To insure further that no radiation coming from a point outside $A'B'$, such as C , may reach T by successive reflection, in addition to blacking the walls of the tube, vanes with circular openings at their center may be inserted so that only the radiation that has passed through the region O is not cut off (allowed to pass). These vanes would also prevent any reradiation of the walls of the tube

¹ *Trans. Am. Electrochem. Soc.*, vol. 17, p. 223, 1910.

to T , even though they may be warmed considerably by the radiation absorbed by them.

2. *Thwing Pyrometer*.—Another type of fixed-focus pyrometer is that proposed by Thwing,¹ a section of which is shown in Fig. 52. The concave spherical mirror is here replaced by a hollow conical mirror at the apex of which is placed the hot junction of the thermocouple. As with the Foster pyrometer, the minimum diameter of the source must be equal to the diameter of the base of the cone whose apex is at O . In practice, the minimum diameter of the source is generally one-eighth that of its distance from O . The vanes prevent radiation from regions outside AB

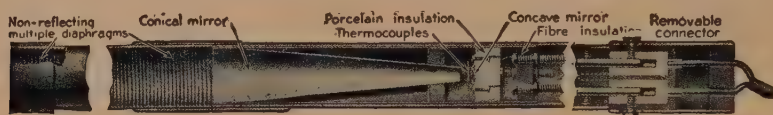


FIG. 52.—Longitudinal section of Thwing total radiation pyrometer. (*Thwing Instrument Co.*)

reaching the mirror, and they also prevent reradiation from any warmed part within the pyrometer tube reaching the thermocouple.

To extend the range of pyrometers of this sort to higher temperatures, the pyrometer tube may be replaced by one in which the area of the opening AB is reduced.

Radiation Pyrometer Sources of Error. 1. *Reflecting Power*.—

All types of radiation pyrometers employ reflectors and the assurance that a calibration is to be of value at a later date implies the maintainence of the reflecting power of the mirror unchanged. As the average pyrometer in shop work is favorably located for the accumulation of dust, care must be taken to insure clean surfaces. The pyrometer tube should be kept closed while not in use and the mirrors should be occasionally cleaned, following the instructions with the instrument. If the coefficient of reflection of the surface has decreased since its calibration it must follow from the Stefan-Boltzmann law that the ratio of the fourth power of the apparent temperature to the fourth power of the absolute temperature is

¹ *Jour. Franklin Inst.*, May, 1908.

equal to the coefficient of reflection of the surface. The magnitude of this correction may be demonstrated by assuming values of the reflecting power and the true temperature. Thus, for a reflection coefficient of 90 per cent at 1500°C. the apparent temperature is about 46° too low.

2. *Absorption*.—As it is very often necessary that the radiation coming to the pyrometer must pass through hot gases and smoke in the neighborhood of the high-temperature source, some of the radiation will be absorbed, and the apparent temperature of the source will be too low. Certain gases, although transparent to visible radiation, exhibit selective absorption of longer wave-lengths to a remarkable degree. A glass window which to visible light offers little absorption is very nearly opaque to the longer wave-lengths. Thus, radiation pyrometers cannot be used where radiation from the source must pass through intervening media of appreciable density.

Emissivity.—The Stefan-Boltzmann law was established for the radiation from the opening of a heated hollow enclosure (black body). The total radiation from a heated mass of metal is always less than that from a black body having the same temperature and area of surface. Hence, the apparent temperature of a mass of metal heated in the open, when measured by a pyrometer calibrated for black-body conditions, is generally less than its true temperature. The total emissivity E may be defined as the ratio between the total radiant energy per square centimeter per second from the body under investigation, to the total energy per square centimeter per second from a black body at the same temperature. Hence, it follows for the apparent temperature of a non-black body that

$$E\sigma T_{\text{true}}^4 = \sigma T_{\text{apparent}}^4$$

or

$$E = \frac{T_a^4}{T_t^4}$$

As demonstrated on page 102, for the selective emissivity E_λ so here also for the total emissivity E , the inside of a hollow wedge

used as a source would emit practically black-body radiation. Thus, the apparent temperature of metals covered with oxide coatings may differ only slightly from their true temperatures. Further, if the metal is in an enclosure, the effect of the wedge may be at least partially obtained so that the apparent temperature may not be greatly in error.

Table VIII shows the apparent temperature of certain sources when the true temperature is as indicated in column 1:

TABLE VIII

True temperature, degrees Centigrade	Apparent temperature, degrees Centigrade		
	Iron oxide coated	Nickel oxide coated	Copper oxide coated
600	572	495	
700	668	600	590
800	763	705	675
900	858	815	755
1000	953	925	850
1100	1048	1035	
1200	1142	1145	...

Range Extension by Variation of Pyrometer-tube Opening.—

For extending the range of a radiation pyrometer, provision is generally made for reducing the area which receives the radiation at higher temperatures. The Féry instrument is arranged so that full area, half area, or indeed any fraction of the total area may be used. For other types, different-sized openings are affixed to the pyrometer tube to alter the range. If A_1 and A_2 denote any two opening areas, then the temperature T_1 for the smaller area is related to the temperature T_2 with the larger area for the same galvanometer reading as follows:

$$A_1 T_1^4 = A_2 T_2^4,$$

giving

$$T_1 = \sqrt[4]{\frac{A_2}{A_1}} \cdot T_2.$$

This relationship has been found to be somewhat inaccurate, due to the different amounts of heat being absorbed by the inner walls of

the pyrometer tube for the two openings and consequently different effects due to reradiation to the thermocouple.

Whipple Closed-tube Pyrometer.—A modification of the Féry pyrometer has been introduced by Whipple in which the pyrometer is placed in the open end of a large fire-clay tube. The other end of the tube is closed and may be placed in direct contact with the body whose temperature is to be obtained. This end, when heated, is the source of radiation for the pyrometer. It is evident that a pyrometer of this sort should possess certain marked advantages. No errors would be present due to the emissivity of the material of the source, variable distance of the source or absorption of intermediate gases, provided the tube is impermeable to gases. This last condition is however difficult to obtain at high temperatures. There is, however, the possibility that the temperature of the end of the tube will not attain the temperature of the source due to the temperature gradient through the refractory wall. This last effect would be largely taken account of in the calibration of the instrument.

Tubes of this sort may often be used to advantage in connection with any type of radiation pyrometer, where the heated body is sufficiently large.

"Pyro" Pyrometer.—This is a recently developed radiation pyrometer which embodies some unique and useful features. Figure 53 is an external view of the instrument. The millivoltmeter, thermo couple and optical system are all incorporated in a single compact unit thus eliminating all cable connections. The instrument is 7" long, $4\frac{3}{8}$ " in diameter and weighs 25 ounces. To make a reading it is only necessary to focus the instrument on the heat source, paying proper attention to the "distance factors" and press the button releasing the indicator. The indicator then swings to the proper point on the temperature scale. By releasing the button the pointer is clamped in this position and the reading may be taken after the instrument is lowered from the eye of the observer.

Figure 54 is a longitudinal section of the instrument. The thermocouple is made up of a very thin wire and a thicker supporting wire. An opaque black disc is fastened to the hot junction



FIG. 53.—The "Pyro" total radiation pyrometer. (*Pyrometer Instrument Co.*)

of the two wires to assist in absorption of the radiations impinging upon it. The hot junction carrying the black disc is mounted in an evacuated bulb. Radiations enter the barrel of the instru-

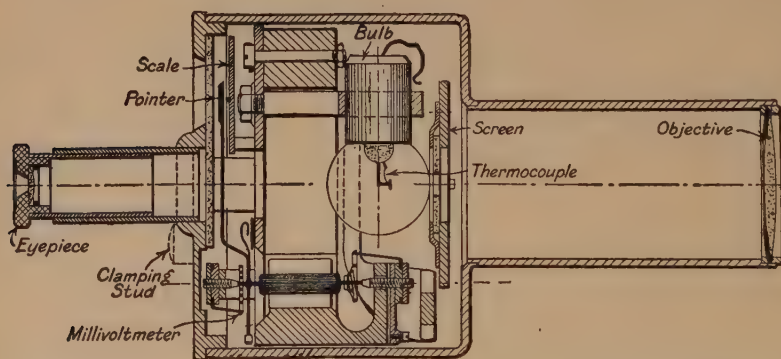


FIG. 54.—Longitudinal section of "Pyro" total radiation pyrometer. (*Pyrometer Instrument Co.*)

ment through the quartz objective lens and are focused upon the hot junction of the thermocouple. By this means greater e.m.fs. are produced in the couple than is usually the case in radiation pyrometers.

EXPERIMENT 1

OBJECT: To calibrate a total radiation pyrometer and obtain its scale law.

Focus the pyrometer upon some high-temperature source of known value. This may be a furnace containing a crucible of some substance whose melting point is known or a broad metal strip heated by an electric current. The temperature of the strip may be obtained by a calibrated thermojunction, a calibrated optical pyrometer or the melting point of a small particle attached to the strip. The metal strip should be placed in an enclosure to insure black-body conditions. The diameter of the heated area should be not less than about one-sixth of the distance to the pyrometer opening. Why?

Féry Radiation Pyrometer.—Making use of the Stefan-Boltzmann law, the scale law for the Féry total radiation pyrometer is shown to be

$$\log (\text{e.m.f.}) = A + B \log T \text{ where } A \text{ and } B \text{ are constants.} \quad (2)$$

Observe the e.m.f. developed in the pyrometer for several known temperatures, keeping the end of the pyrometer tube completely open. Taking any two of these, calculate A and B . Now solve for some of the other temperatures from the e.m.f. readings. Do the calculated and observed values of T agree? Suggest possibilities for disagreement. Show the observed and calculated values graphically, using $\log (\text{e.m.f.})$, and $\log T$ as coordinates. Explain the focussing device of the Féry instrument and state the importance of correct focus. Repeat some of the readings with the pyrometer opening half closed and three-fourths closed. Calculate the e.m.f. that should be obtained for these last readings?

Thwing Total Radiation Pyrometer.—How does the scale law of the Thwing pyrometer differ from that of the Féry pyrometer. Obtain results as outlined in previous paragraph, and check results similarly.

Observe the effect of absorbing media by interposing a glass plate between the pyrometer and high-temperature source. Explain why the effect is so much more noticeable than with the optical pyrometer.

Study the effect of distance by placing the pyrometer successively at increasing distances from the fixed temperature source. Explain results with a figure.

Would a heated platinum strip give the same apparent temperature in the open as when enclosed? Why?

Problems

1. In a Féry total radiation pyrometer, e.m.f. values of 0.5 and 2.5 millivolts are developed at temperatures of 1135°C. and 1765°C. respectively. What temperatures should correspond to 2 and 3.5 millivolts? Give both the calculated and the observed results.

2. Using the Stefan-Boltzmann law, compare the relative power supply to a furnace to maintain temperatures of 1500 and 2500°C.

3. The normal radiation intensity of the sun at the earth is 2 calories per cm.² per minute. What does this mean for the radiation per cm.² per minute at the surface of the sun, assuming it to be a black-body radiator? Calculate its temperature.

$$W = \sigma A(T_1^4 - T_2^4),$$

$\sigma = 5.709 \times 10^{-12}$ when W is joules per second.

4. To what temperature would the blackened spherical bulb of a thermometer rise if exposed to the radiation of the sun when the temperature of its surroundings is 25°C.?

5. What daily temperature range might be expected on the equator of the moon? The length of the day on the moon is 28 days.

6. What should be the ratio of the open to the total area in a radiation pyrometer when sighted upon melting palladium 1550°C., in order that the same reading is obtained as when used with the total space open with melting gold 1063°C.?

7. A radiation pyrometer when sighted upon a molten metal surface indicates a temperature of 1040°C. while a standard thermocouple gives the temperature as 1150°C. What is the emissivity of the surface?

8. A certain coating of dust upon the conical mirror of a Thwing radiation pyrometer reduces its coefficient of reflection to 95 per cent (for all wave-lengths) of the value for which the pyrometer was calibrated. Thus when the pyrometer reads 1500°C., what is the true temperature?

CHAPTER VII

TEMPERATURE RECORDERS AND CONTROLLING DEVICES

In both the laboratory and the plant, many operations require continuous and permanent records of temperature. In careful experimental work it is often very helpful to operate a recorder in conjunction with other more sensitive instruments being used to make temperature measurements. In this way a constant check can be maintained, since any large variance between the two instruments would be immediately evident and the cause investigated. The applications of recorders in plant work are numerous, on account of the fact that any operation or series of operations is made more efficient by the use of permanent records of past performance. In furnace work, it is thus possible to have ready information regarding the work of different shifts, rates of heating and cooling, time at heat, variations while at heat, comparison of fuels, and continuity of operation. In some of the large plants maintaining heat-treating departments the number of recorders runs into the hundreds.

One of the greatest benefits accompanying the use of pyrometers is the improved control of furnace temperatures. Several methods of control have been used, but since the present tendency seems to be distinctly in the direction of automatic control by recording instruments, the consideration of this whole subject will be taken up later in this chapter.

TEMPERATURE RECORDERS

Types of Pyrometers Which Can Be Made Recording.—All pyrometers can be made at least semirecording, but the ones which lend themselves most easily to automatic recording are the

fluid thermometers, thermoelectric pyrometers, resistance thermometers, and radiation pyrometers.

Fluid Thermometers.—The constant-volume gas thermometer is easily made recording by connecting a registering manometer with the bulb of the thermometer (see Fig. 2). The calibration of this type of recorder is difficult and inaccurate. There are, however, several commercial fluid-thermometer recorders which are being used successfully. The record is made by means of a pressure indicator which carries an inked stylus. The stylus rests against a sheet of paper which moves either in a linear or

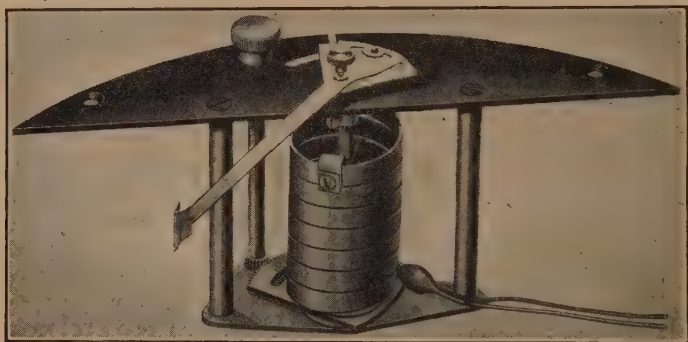


FIG. 55.—Mechanism of a recording pressure thermometer. (*Brown Instrument Co.*)

circular direction. This paper is usually actuated by a clock. As the temperature varies the indicator carrying the stylus moves back and forth over the sheet, leaving a line which is a record of the variation of temperature with time. Figure 55 represents the indicator mechanism in one of these instruments. As the pressure in the bulb increases, the hollow helical spring opens out, causing the indicator arm to move through a fairly long arc. Figure 56 represents the complete assembly of the recorder with the stylus drawing a curve on the paper. Figure 57 represents the bulb of such a recorder installed in a pipe line. This bulb contains the non-compressible fluid, the expansion of which causes the movement of the recorder needle.

In this connection might be mentioned the recording thermometers of the bimetallic strip type. If strips of two metals having different coefficients of expansion are fastened together and heated,



FIG. 56.—Recording pressure thermometer. (*Brown Instrument Co.*)



FIG. 57.—Bulb of a pressure thermometer installed in a pipe line. (*Brown Instrument Co.*)

the strip tends to straighten out if in the form of a spiral, or to bend if in a straight section. This movement may be used in causing an indicating arm to move through an arc. The use of this type of instrument is somewhat limited.

The range of all such instruments as have just been described is below 1000°F. There might be an advantage over thermoelectric and resistance pyrometers in that they are independent of all electrical circuits.

Thermoelectric Recorders.—As discussed in Chap. III there are two types of indicators used in thermoelectric pyrometry, the millivoltmeter and the potentiometer. It follows that there are two corresponding types of recorders. Each type of recorder is subject to the same limitations as the indicating instrument from which it was developed.

The records made by these instruments are time-temperature curves and in the millivoltmeter type of recorder are made by periodically impressing some sort of mark upon a paper which is either traveling in a linear or circular direction. The potentiometer type of recorder may draw a continuous curve. If a circular record is made, the time between renewals of the paper is shorter than when a continuous roll chart is used. Circular record sheets are usually replaced every 24 hours, while a roll chart may last for a month, the record for each day being torn off and filed if desired.

The Millivoltmeter Recorder.—Figure 58 illustrates in a simple manner the fundamental operations of this type of recorder. *P* is the record paper which is caused to pass gradually forward or downward under the galvanometer needle *N*. *N* carries some sort of stylus. *B* is a depresser or chopper bar which at stated intervals is caused to move against the needle *N*, carrying it into contact with the paper. In some cases the stylus carries ink and thus leaves a dot upon the paper directly. In other cases the stylus merely causes a contact between the paper and an inked ribbon or thread. A series of dots which are so close together as to give the appearance of a continuous curve is thus formed. The operation is necessarily intermittent, since the needle must be given an opportunity to swing freely to its proper indicating positions. The chopper bar is actuated in some cases by clockwork, in other cases by an electric motor or an electromagnet. In any event the

mechanism must work in such a manner that no damage is done to the galvanometer coil mounting. This means that the construction must be somewhat more rugged than in portable indicators. Usually the resistance of a recorder is a little less than that of an indicator of the same type, and the magnetic flux is increased by using more magnets.

It is possible to produce more than one record on the same recorder. This is accomplished by introducing an automatic

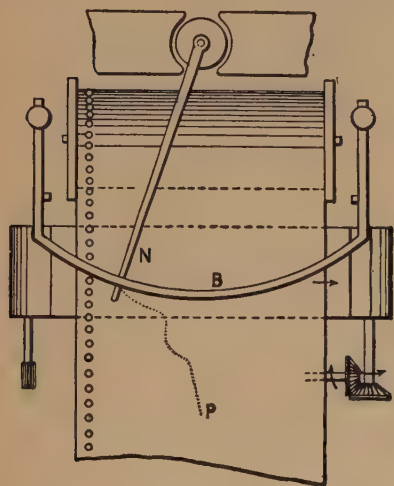


FIG. 58.—Fundamental parts of the millivoltmeter recorder. (T. P. 170 U. S. Bur. Stand.)

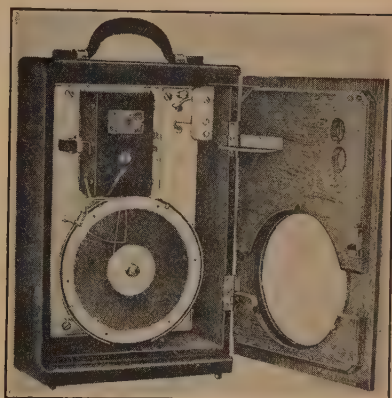


FIG. 59.—Millivoltmeter recorder with circular chart. (The Bristol Co.)

commutating switch into the instrument. By this means several thermocouples may be connected in rotation to the recorder. As each couple in turn is connected to the instrument, the needle swings to its new position and leaves a dot or dash. It is rather difficult sometimes to distinguish similarly formed records, and in order to eliminate this, several features have been introduced. In some instruments different colored ribbons or threads are used, each one being brought into position by the movement of the commutating switch. Thus, each record is made in a different color. Another scheme is to vary the time of contact of the stylus

with the paper. By this means several combinations of dots and dashes may be secured.

Figure 59 represents an instrument which makes a circular record. The hours of the day are upon the margin of the paper. The galvanometer needle and chopper bar are suspended in front of the paper. The paper has a smoked surface and the stylus

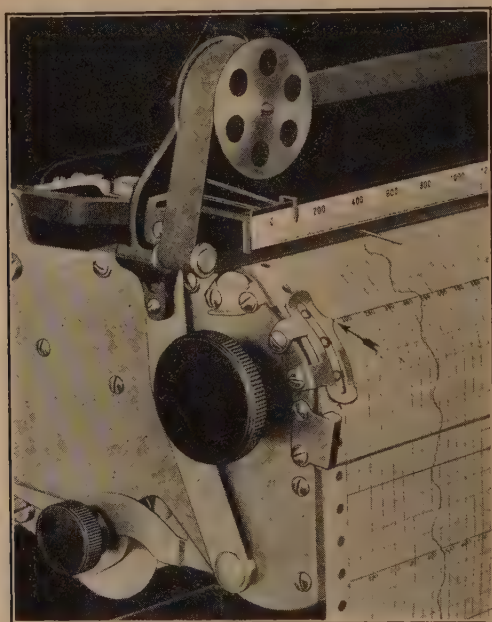


FIG. 60.—Recording point of a roll chart millivoltmeter recorder. (*Brown Instrument Co.*)

coming in contact with it leaves a series of white dots. After the removal of the chart from the instrument, the sheet is dipped in a fixing solution which renders the record permanent. Figure 60 is a close-up view of the recording point of a roll-chart type of recorder. The chopper bar, inked ribbon, and galvanometer needle are clearly shown. Arrow indicates index for timing the chart properly. Figure 61 is an assembled view of the recorder mechanism. The instrument is operated by either a hand-wound clock or a synchronous electric clock.

Many types of millivoltmeter recorders are on the market but the underlying principle of operation is the same in all. The individual differences and refinements are usually evident upon inspection of the various instruments and will not be discussed here.

The Potentiometer Recorder.—Readings on a null-point potentiometer are taken by balancing the unknown source of e.m.f.

against a portion of a known e.m.f. In a manually operated potentiometer, the observer moves the contact back and forth until the galvanometer comes to rest, indicating an exact balance between the two e.m.fs. If such an instrument is to be made automatically recording, it is evident that the

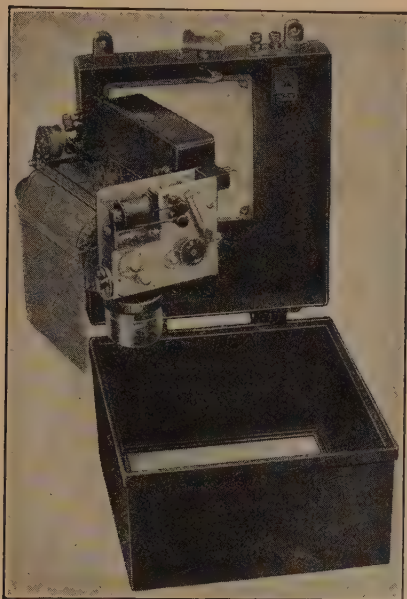


FIG. 61.—Millivoltmeter recorder. (Brown Instrument Co.)

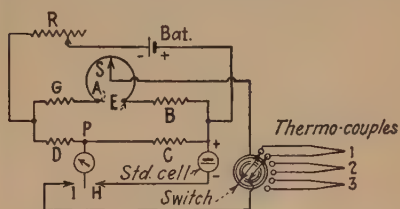


FIG. 62.—Measuring circuit of a potentiometer recorder. (Leeds and Northrup Co.)

departure of the galvanometer from the position of balance must be made to actuate a mechanism which will move the contact point closer to the position of balance.

Figure 62 represents the wiring in the measuring circuit of a potentiometer recorder. It is of the split-circuit type, as is evident from the diagram. The checking of the main battery current against the standard cell is accomplished by closing contact *I* and adjusting rheostat *R*. This may be done manually or automatically, as will be brought out later. The deviations of the galvanometer from its zero position cause the contact *S* to move to

such a position that the galvanometer will be balanced. The movements of point *S* are translated into a linear movement of an inked stylus across a roll of paper which is moving in a direction perpendicular to that of the stylus.

Figure 63 is the front view of such a recorder in operation. The square panel at the left inside the case carries a push switch (at

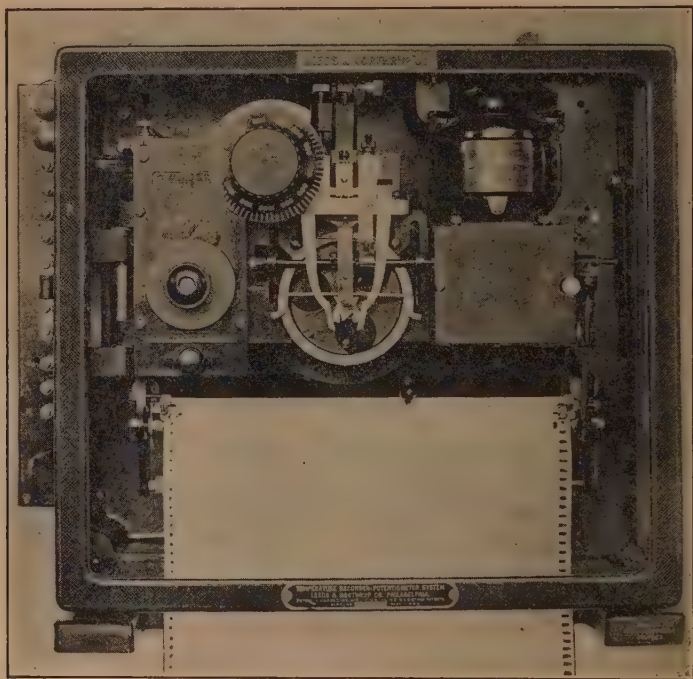


FIG. 63.—Potentiometer records—Front view. (*Leeds and Northrup Co.*)

bottom of panel) and the rheostat for manually checking against the standard cell. This check should be made at least once a day when the instrument is in continuous operation. In the center is found the balancing mechanism and at the right is the small electric motor with speed governor which operates the balancing mechanism. At the bottom of the case is the chart upon which the record is made. The chart is gradually unrolled at a constant speed by means of a gear train from the motor shaft, thus causing

a line to be drawn by the inked stylus whose point is resting on the paper.

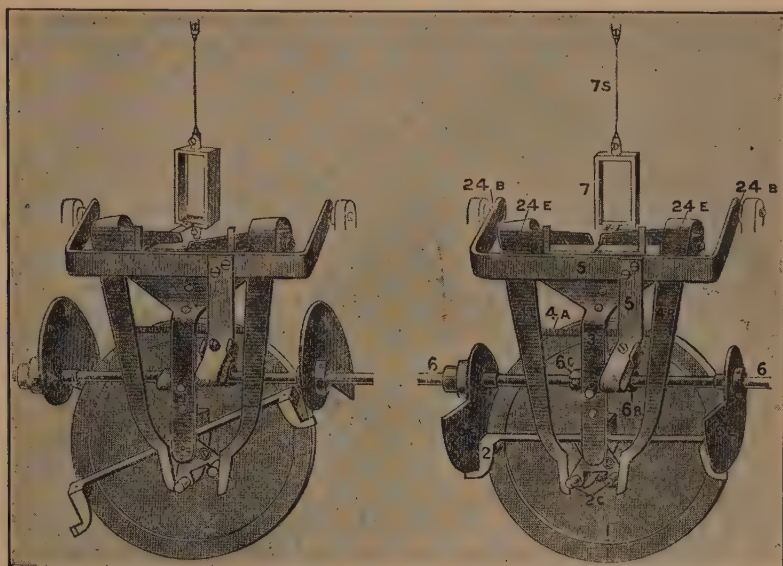


FIG. 64.—Balancing mechanisms of potentiometer recorder. (Leeds and Northrup Co.)

The operation of the balancing mechanism will be described in detail. Disc 1 in Fig. 64 is mounted on the same shaft as the disc

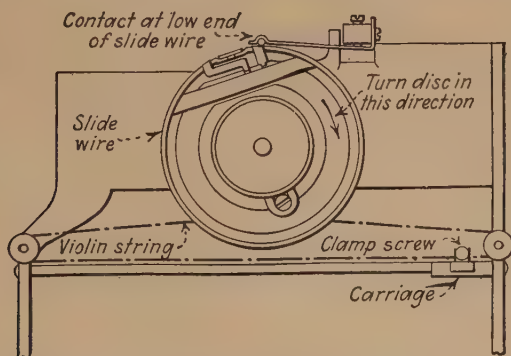


FIG. 65.—Slide wire disc with contact. Potentiometer recorder. (Leeds and Northrup Co.)

which carries the slide wire *AE* in Fig. 62. This slide-wire disc with contact is shown in Fig. 65, which is a diagrammatic view from the rear of the instrument. Around this slide-wire disc passes

a violin string to which the pen carriage is fastened. The position of the violin string and the manner in which it causes the pen carriage to move back and forth are evident from Fig. 65. Any movement, therefore, of disc 1 on the front of the instrument will cause the slide-wire disc to move. This in turn will change the position of the contact and the pen. Referring to Fig. 64, it is seen that the galvanometer swings in a slot over rocker arm 5 and under the right-angle levers 4*L* and 4*R*. When the galvanometer is balanced at the mid point of its arc, the needle is directly under the open space between the ends of the right-angle bars 4*L* and 4*R*, which are pivoted at 24*E*. In this position the rocker arm 5 in rising will lift the point of the needle into this open space and no change in the position of the other parts will occur.

Shaft 6 carrying cams 6*E* is driven by the motor and rotates in such a direction that cams 6*E* are always tending to bring bar 2 to a horizontal position. Bar 2 carries at each end on the inner side, a cork pad which rests tightly against the outer rim of disc 1, unless pushed forward against the tension of spring 3 by cam 6*C*. Spring 3 is attached rigidly to the frame of the instrument. Rocker arm 5 is lifted by cam 6*B*.

The movements in the mechanism caused by a swing to the left of the galvanometer needle will now be considered in order. A swing to the right causes the same movements, only in the opposite phase. Rocker arm 5, lifted by cam 6*B*, lifts the needle against the right-angle arm 4*L*. The lower arm of 4*L* is thus moved to the right, carrying lug 2*C* with it. Lug 2*C* is fastened securely to bar 2, the whole assembly being free to turn about an axis above the contact point of 4*L* with 2*C*. This contact was made while bar 2*C* was out of contact with disc 1. The whole mechanism is now in the position shown at the left in Fig. 64. Cam 6*C* now moves down, allowing the cork contacts of bar 2 to rest against disc 1. Cams 6*E* come around and force bar 2 back to the horizontal position. Bar 2 being in close contact with disc 1 is turned in a clockwise direction. This moves the sliding contact on the back of

the instrument nearer to the position of balance. The operation is repeated until the galvanometer needle is not deflected but merely lifted into the space between arms $4L$ and $4R$. The pen has then been moved to the point on the chart which indicates the correct temperature or millivoltage.

The amount of rotation given to arm 2 and disc 1 depends on the extent of the galvanometer deflection, since the needle approaches the fulcrum of the lever as the deflection increases. Ordinarily, the rebalancing steps of the recorder pen vary by uniform gradations from $\frac{1}{50}$ to $\frac{3}{4}$ inch. Thus, large variations may be followed rapidly and small ones accurately. The rotation of the shaft 6 takes about 2 seconds, which gives ample time for the galvanometer to assume its new position after being released by rocker arm 5. The full scale of the instrument may be varied from 10 to 80 millivolts by the use of suitable shunts. If temperature alone is indicated on the scale the calibration is made according to the temperature—e.m.f. relation of the particular thermocouple to be used.

In some cases the standard cell check is made automatically. It is then necessary to place on the main shaft a disc which carries resistance R in Fig. 62. At stated intervals a commutating switch breaks the contact s at points S and H and closes those at points R and I . Movements of disc 1 (Fig. 64) then result in varying the resistance in the battery circuit until the standard cell is correctly balanced.

The instrument can be made to record the temperatures indicated by more than one couple by introducing a commutating switch and a mechanism for depressing and lifting the print wheel from the paper. The commutating switch connects each couple with the instrument for a period of time, long enough for the print-wheel carriage to be brought to its proper position and a record made. The print wheel revolves in synchronism with the commutating switch so that when it is depressed the record on the paper consists of the number of the thermocouple and a large dot.

The line of dots thus formed is the record of the variations of that particular thermocouple. The print wheel and the commutating switch are actuated by a gear train from the motor. The print wheel is inked by a pad which is constantly in contact with it. This pad must be saturated with ink every few days.

Recorders for Resistance Thermometers.—There are two types of recorders for use with resistance thermometers, one employing the balanced Wheatstone bridge and the other the

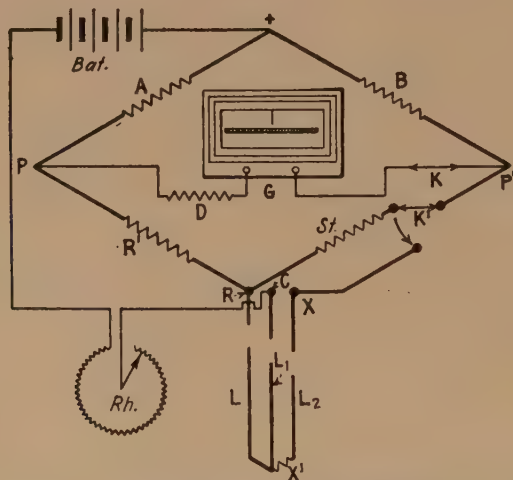


FIG. 66.—Wiring diagram of resistance thermometer recorder using the unbalanced Wheatstone bridge. (*Brown Instrument Co.*)

unbalanced Wheatstone-bridge method of measuring resistance (see Chap. IV, Resistance Thermometers). Figure 66 represents the wiring diagram of a recorder using the unbalanced Wheatstone-bridge principle. Switch K' is first placed in the position shown on the diagram. The rheostat Rh is then adjusted until the galvanometer needle is brought to some arbitrary point. Switch K' is then swung over to the position indicated by the arrow. The galvanometer then swings to a point representing the temperature (in terms of resistance) at point X' . Any variation in temperature will be indicated by movements of the galvanometer. It is possible to construct the instrument in such a manner that the galvanom-

eter will cover any desired range up to 1000°F . The battery-current adjustment described above is made every day or two.

From what has been said in the preceding paragraph it is evident that the temperature is indicated by a galvanometer needle in precisely the same manner as in the millivoltmeter used with a thermocouple. It is therefore possible to record the temperature with the same type of instruments as are used in thermoelectric recorders of the millivoltmeter type, the principle and operation of which have been described earlier in the present chapter.

Figure 67 represents the wiring diagram of a recorder using the balanced Wheatstone bridge for measuring resistance. As may be seen, this circuit involves the use of a double slide wire. All the moving contacts are in the galvanometer or battery circuits and, therefore, cannot affect the accuracy of the measurement. The two slide wires S and S_1 and the contacts V and V_1 are placed side by side in the instrument. V and V_1 , therefore, are made to move simultaneously. The two slide wires are electrically

so proportioned that at all points the resistance A_1V_1 is equal to resistance VV_1 , thus keeping the ratio arms of the bridge at unity. As the contacts V and V_1 move, however, the resistance VB varies and, since VV_1 always equals A_1V_1 , the bridge will be balanced when $VC_1 = C_1A$, or when the variable resistance VC_1 equals the resistance in the thermometer bulb T . The proper proportioning of lead wires has been previously discussed. By properly calibrating the slide wire S , which makes up the variable section of the resistance VB , the setting will read in terms of temperature at T instead of ohms.

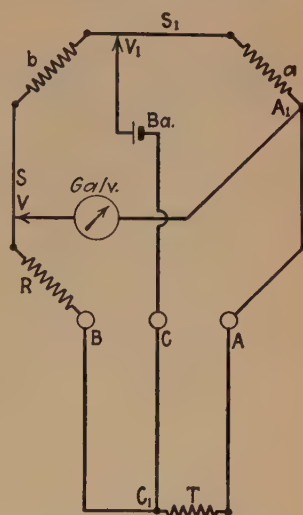


FIG. 67.—Wiring diagram of resistance thermometer recorder using the balanced Wheatstone bridge. (Leeds and Northrup Co.)

This kind of a measuring circuit can be made recording by the use of an instrument exactly similar to the potentiometer recorder already discussed in this chapter. Slide wires S and S_1 are mounted side by side on the disc at the rear end of the main shaft (see Fig. 65). The departure of the galvanometer from its balanced position will then cause the balancing mechanism to turn the disc until a point of balance is obtained. The chart is usually calibrated in terms of temperature and may be made to cover any desired range up to 1000°F .

Radiation Pyrometers.—Since the readings of total radiation pyrometers are made in terms of e.m.f. developed by sensitive thermocouples, permanent records may be made by the use of either millivoltmeter or potentiometer recorders, and used in connection with them. The only variation will be in the temperature—e.m.f. relationship, and this is merely a matter of proper calibration.

CONTROLLING DEVICES

The control of furnace temperatures as herein considered, involves the heating and cooling of the furnace between two points, the distance between which is determined by the requirements of the process. In some cases, it is very essential that temperature be held as nearly as possible at a single point. Where this is necessary, the range of variation may be as small as 2 or 3°C . In other cases a variation of 25°C . may be entirely sufficient. In any event, control is secured by alternately increasing or decreasing the amount of heat being supplied to the furnace. It is sometimes accomplished by completely shutting off and turning on the source of heat. In research laboratories much closer control is sometimes required, but this is secured by increasing the sensitivity of the device rather than changing the principle of operation.

Controlling devices naturally fall into two large classes: that in which a signal is given the furnace operator and that in which the controlling device automatically makes the adjustments of valves

or switches which are required to hold the furnace in a given temperature range. The first class has two divisions, one wherein the signal is given manually to the furnace operator by a central-station observer, and one wherein the signal is given automatically.

Signaling. *Manual Signaling.*—Figure 68 illustrates the central-station equipment for a manually operated signaling system. The indicating instrument, in this case a potentiometer, is connected to a large number of thermocouples through a selector switch-

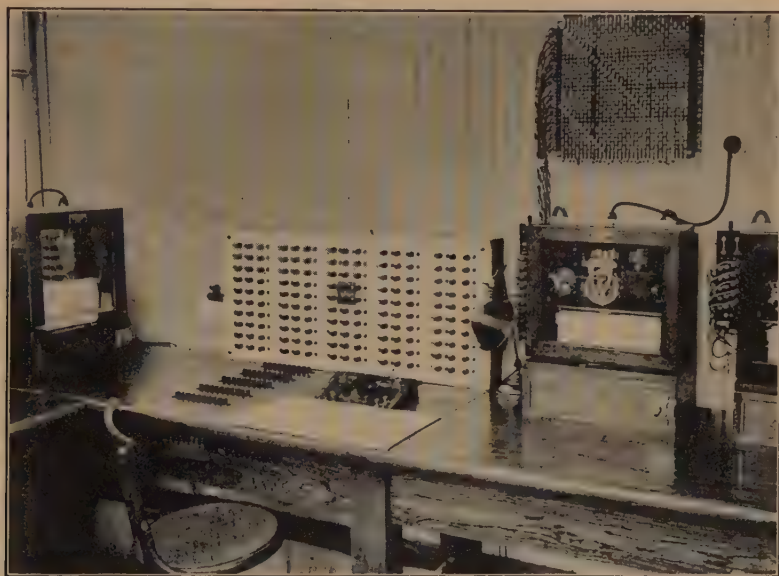


FIG. 68.—Equipment for manual signaling. (Leeds and Northrup Co.)

board. If the pyrometric system is not large, one switchboard will suffice, but in a good many plants it is necessary to have several switchboards and a corresponding number of operators. Each thermocouple circuit is equipped with a push-button switch on the board and at regular intervals the central-station operator closes the switches and reads the temperatures indicated. He then, by means of a signaling system, advises the furnace operator of the condition of the furnace. This signal is usually given by means of colored lights, although telephones and pneumatic tubes are sometimes used. An annunciator is occasionally used to enable the

furnace operator to advise the station operator that he desires a reading made.

The colored lights are placed on a panel above or at one side of the furnace. A red light indicates the furnace temperature is too high, a white light that it is correct, and a blue or green light that it is too low. Various combinations and code signals can be worked out which will indicate the approximate departure of the furnace from the desired temperature. The furnace operator, upon

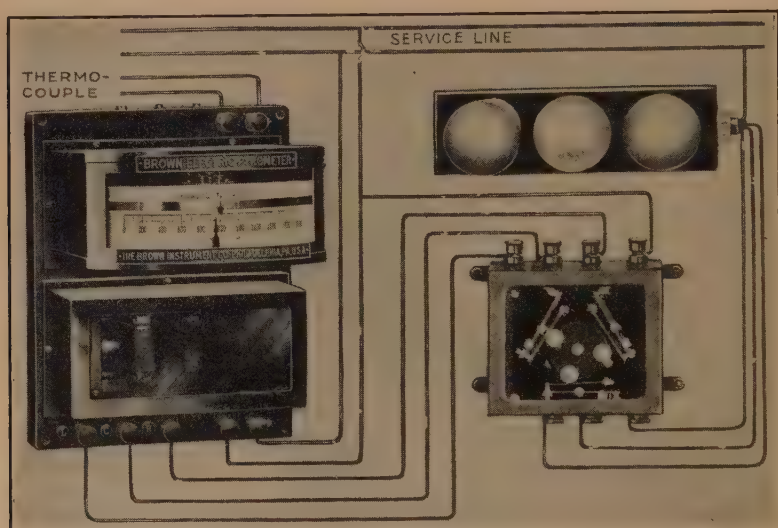


FIG. 69.—Automatic signaling pyrometer. (Brown Instrument Co.)

noting the signal received from the central-station operator, makes a suitable adjustment if necessary of the valves or switches to bring the furnace back to the correct temperature.

Automatic Signaling.—An automatic signaling system eliminates the central-station operator, but not necessarily the central station, since there are many advantages in locating all the signaling instruments in one room. Both the millivoltmeter and the potentiometer types of instruments may be made to operate a bank of signal lights automatically.

Figure 69 represents an automatic signaling pyrometer of the millivoltmeter type. Red, white and blue lights are used. Mounted

on an arm which is free to swing across the scale are two sets of platinum contacts which determine the signaling range. This arm is placed in such a position that the point midway between the two sets of contacts is at the desired temperature. As in the case of the recorder, this instrument is equipped with a depressor or chopper bar. At short intervals this depressor bar pushes down the galvanometer needle. As long as the needle remains nearly at the correct temperature, the white light is on. If the temperature rises or falls slightly, the needle will swing over that corresponding set of platinum contacts. When it is next depressed, the two points of the contact will be pushed together and thereby close a relay circuit which causes an electromagnetic switch to disconnect the white light and turn on the red or blue light. The range over which the white light burns is in this instrument about 20°F. although it may be changed to meet other requirements.

Figure 70 represents the circuits in a signaling potentiometer recorder with deviation meter. The deviation indicator shows in degrees Centigrade or Fahrenheit the exact departure of the furnace from the desired temperature. The deviation indicator as well as the signal lights are operated by an external circuit, preferably a 110-volt alternating current. The deviation indicator is a Wheatstone bridge, the deviations being given by the deflections of the galvanometer. The discs carrying the slide wire of this Wheatstone bridge and the contacts for the signal lights are all mounted on the main shaft of the recorder, and may be loosened and set for any desired signaling range. As the temperature varies, the balancing mechanism of the recorder rotates the discs, which results in connecting the proper light and causing the deviation indicator to move to the right or left through the unbalancing of the Wheatstone-bridge circuit.

Automatic Temperature Control.—The construction of instruments for automatic temperature control is very similar to that of the signaling instruments. In the latter case the relays actuate lighting circuits while in the former the secondary circuit con-

tains devices for changing the position of valves or switches which control the heating units of the furnace. Three typical instruments will be discussed.

Millivoltmeter Control.—Figure 71 represents the interior construction of a control pyrometer of the millivoltmeter type. *J* is an adjustable table carrying the contact points. The distance between the contact points represents the range over which con-

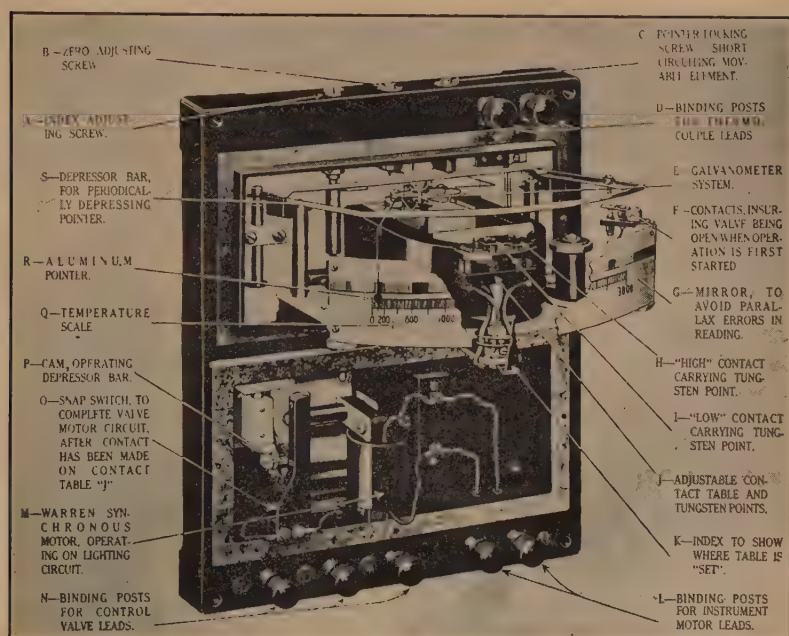


FIG. 71.—Control pyrometer of the millivoltmeter type. (Brown Instrument Co.)

trol is secured. The contact table can be swung to any position on the scale. The needle *R* has a small projection on the outer end of the horizontal portion and whenever this projection is exactly over the contact points, the lowering of the depressor bar will cause it to close the contact and to actuate the fuel valve through a relay. If electric heat is being used, the closing of the contacts opens or closes a switch in the heating current circuit.

The actual cycle of operations is as follows: When the furnace is started, it will continue to heat up until the pointer closes contact *H*. It will previously have closed contact *I*, of course, but since the valves were already open they would not have been changed. When contact *H* is made, the valves are closed and the furnace begins to cool off. After a short period of cooling, contact *I* will be made, the valves will be opened again, and the furnace heated until contact *H* is reached. When either contact is made, it automatically opens the circuit which has been closed by the other contact.

Potentiometer Control.—Figures 72 and 73 represent the circuits in the Leeds and Northrup control potentiometer. Discs *L* and *H*

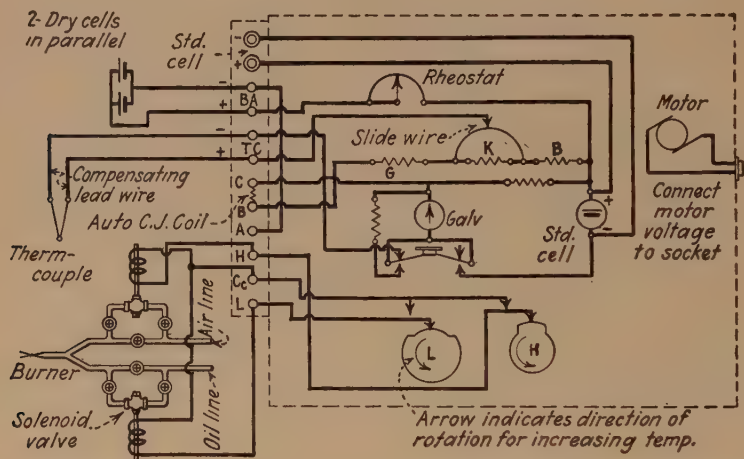


FIG. 72.—Potentiometer control circuit for oil or gas furnaces. (Leeds and Northrup Co.)

are carried on the main shaft and as shown in the figures are rotating in the directions indicated by the arrows. When this rotation has continued for a short time, the slopes of the edges of the discs change in such a way that the contact on *H* will be broken and that on *L* closed. This reverses the position of the solenoid valves or switches. Figure 74 is a view of such a controller when swung out of the case, showing the control contacts and the discs that operate them. The discs are fastened to the shaft with set

screws so that they may be loosened and placed in proper position for control over any desired range.

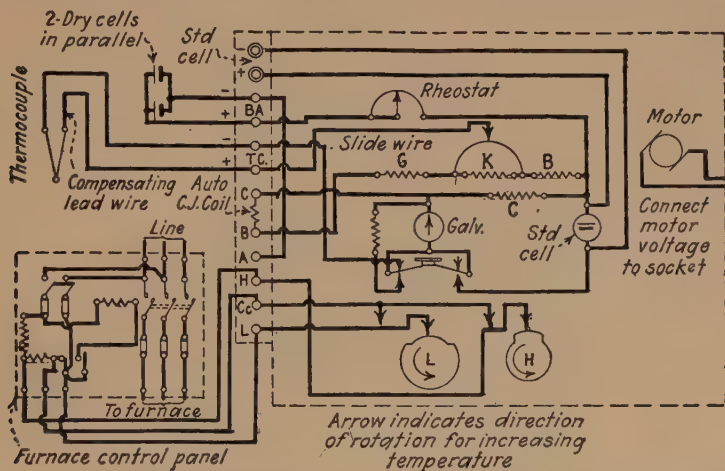


FIG. 73.—Potentiometer control circuit for electric furnace. (Leeds and Northrup Co.)

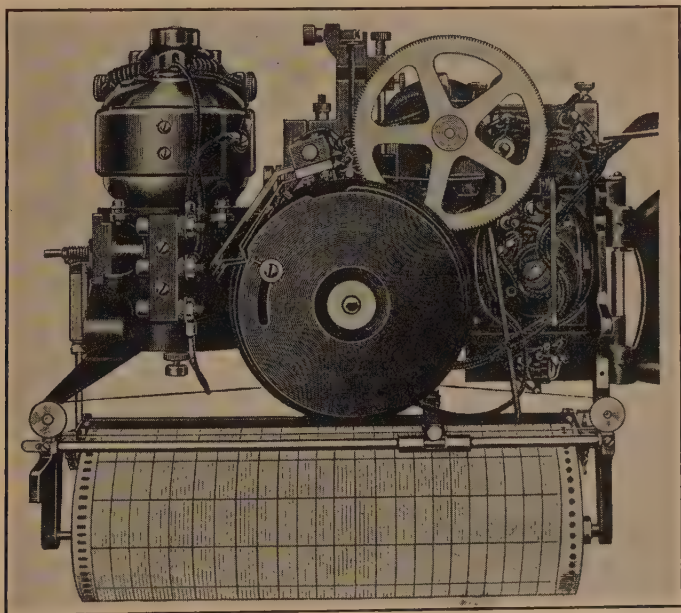


FIG. 74.—Potentiometer control. Rear view of instrument showing control contacts and rotary discs. (Leeds and Northrup Co.)

Figure 75 is a controller with a potentiometer circuit developed by the Wilson-Maeulen Company. In this instrument the sliding

contact does not move, but is set at the desired temperature by means of the large dial at the upper end of the panel. The galvanometer (whose pointer is seen through the window in center of the panel) indicates departures from the temperature for which the main dial is set. On the horizontal portion of the pointer which is immediately above the scale, there is a small rectangular



Fig. 75.—Potentiometer controller with sliding contact stationary. (Wilson-Maculen Co.)

block, which regulates the distance through which the chopper bar oscillates. The chopper bar is seen at the right of the galvanometer pointer. Fastened to the chopper bar are three wipe contacts, the upper two or the lower two of which are shorted by a button on a rotating disc, depending upon the position of the three wipe contacts. As long as the galvanometer pointer is on the

“low” side the chopper bar falls through its complete arc and contact is made between the upper two of the wipe contacts previously mentioned. This keeps the valves or switches in such a position that the furnace continues to heat up. As soon as the pointer passes over to the “high” side, the small block on the pointer moves under the chopper bar and prevents it from moving through its complete arc. This brings the lower two of the wipe contacts in such position that they are shorted by the button on the rotating disc. This actuates the relay on the “high” circuit, causing the furnace valves or switches to be closed.

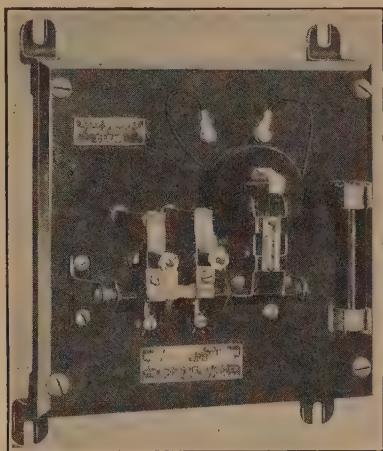


FIG. 76.—Control panel for electrically heated devices. (*Brown Instrument Co.*)

These units are constructed in such a manner that several of them can be connected in series and driven by a single motor. The minimum range of control is about 2.5°F .

Control Valves and Switches.—Figure 76 is a control panel for electrically heated devices. The relay and magnetic switch are shown. When the contact at the “low” point is made, the relay closes, in turn closing the magnetic switch. The relay is opened at the “high” point by short-circuiting the current in the holding coil. Figure 77 is a motor-operated control valve for use on oil, gas, air, or steam lines. The various parts are clearly indicated. When

contacts on the controller are made, the motor *B* is started and through a crank mechanism moves bar *Q* to the proper position for opening or closing the valves. The position of the valves is controlled by limit switch *O*.

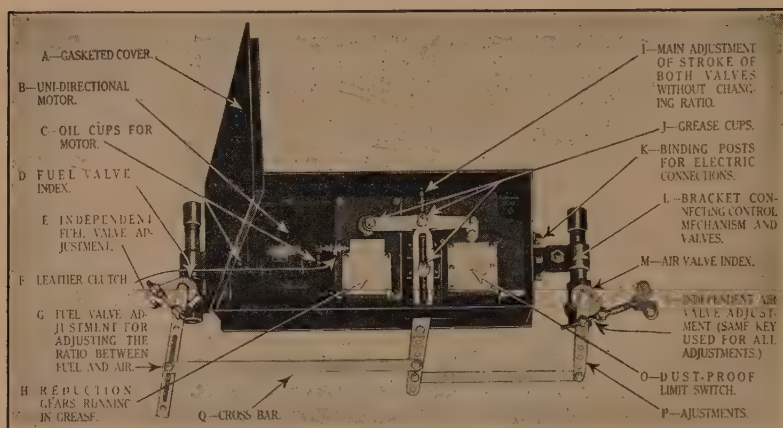


FIG. 77.—Motor operated control valve for oil, gas, air or steam lines. (*Brown Instrument Co.*)

EXPERIMENT 1

The Recording Millivoltmeter

a. Observe the instrument in operation until the purpose and relation of all parts are clear. Sufficient notes should be taken to pass satisfactorily an oral quiz on the mechanical operation of the instrument and the location of the various parts of the electrical circuits, both measuring and auxiliary.

b. Calibration.—Using a battery box or some other means of obtaining a variable e.m.f. check readings at regular points on the scales (if more than one) against a potentiometer. Construct a correction curve for each scale. If there are errors in the readings, state possible reasons for their occurrence and what might be done to correct them.

EXPERIMENT 2

The Recording Potentiometer

a. Same as Experiment 1.

b. Calibration.—In calibrating one potentiometer against another it is unnecessary to employ an external source of e.m.f. Why? In checking the scales of a recording potentiometer, therefore, it is only necessary to connect the

corresponding terminals of the two instruments. A portable potentiometer is sufficiently accurate for checking. Short-circuit the galvanometer on the recorder, and turn the balancing mechanism to such a position that the clutch is released. This allows the main shaft to be rotated freely to any position. By thus rotating the shaft, set the pen indicator at various points on the scale and check against the portable instrument. Prepare a correction curve for each scale and give possible reasons for any errors found.

EXPERIMENT 3

The Recording Resistance Thermometer

a. Same as Experiment 1.

b. Using an oil bath which can be heated over a range of several hundred degrees fahrenheit, check the readings of the recorder against a standard thermocouple or fluid thermometer which is tightly attached to the resistance thermometer bulb. Be sure the bulb is properly immersed. Prepare a correction curve and give possible reasons for any errors found.

EXPERIMENT 4

High-temperature Control

Using a recorder with control attachment, assemble an apparatus for automatic control of either a small electric resistance or gas-fired laboratory furnace. Make a drawing of the set-up and write a brief description of its operation.

If an automatically controlled gas, oil, or electric furnace is not available in the laboratory, it is frequently possible to visit a near-by plant which operates one. Study the operation of the control apparatus and prepare a drawing which shows the relative positions of all electrical and mechanical parts of the equipment. Write a brief description of its operation, indicating the type of controller and the types of valves or switches used and the range of control.

CHAPTER VIII

TRANSITION POINTS AND THERMAL ANALYSIS

All substances may exist in three different physical states—liquid, solid, and gaseous. Provided suitable means of supplying or removing heat are available, the pressure remaining at a suitable value, it is possible to cause substances to pass from one state to another. The temperatures at which such changes take place are termed “transition points.” While the change in state is taking place the temperature may remain stationary or nearly so, as long as the two phases of the substance are present. Molecular or atomic rearrangements may take place in a substance while it remains in a single physical state, such as the allotropic changes in phosphorus and carbon, the change from eutectoid to solid solution in steel, or from one solid solution to another in some non-ferrous alloys. The temperatures of these are also transition points. Many minerals exhibit transitions of one kind or another.

All substances exhibit various physical and constitutional changes as they pass through a transition point. There is one phenomenon, however, which is always present, namely, the absorption or evolution of heat. The different phases of a substance have different energy contents, but those stable at higher temperatures have greater energy contents than those stable at lower temperatures. This is in accord with the proposition that all natural processes take place in such a way that the potential energy of the system approaches a minimum. It follows, therefore, that when a higher temperature phase passes to a lower, there will be an evolution of heat, and *vice versa*. The heat evolved as vapor changes to liquid is called the latent heat of vaporization, and as liquid changes to solid the latent heat of fusion.

It is this evolution or absorption of heat which maintains the temperature of the system nearly stationary while the change is taking place.

The determination of transition points is clearly a problem in temperature measurement. Many determinations of boiling and melting points can be observed directly with a thermometer or pyrometer. In many cases, particularly those where changes are taking place without change of physical state, it is necessary to locate the transition points by means of cooling curves. Some transitions do not take place sharply at certain temperatures, but extend over certain ranges of temperature.

Importance of Transition-point Determinations.—The determination of transition points has become such an important phase in the study of the constitution of substances, particularly alloys, that it has been dignified by the name of “thermal analysis.” It is scarcely necessary to point out the importance of knowing the boiling and melting points of elementary substances and compounds. They form two of the most important groups of constants which the physical sciences use. The equilibrium diagrams which are so useful in metallurgy, as well as in other branches, are nothing but maps of melting point and constitutional variation as shown by determining the location of the transition points in a series of alloys or complex compounds.

The occurrence of transition points in solid substances, particularly alloys, makes possible in some cases a variation of physical properties of the substance through heat treatment. Different phases of the same system often show very marked variations in strength, hardness, corrosion resistance, etc. If an alloy is suddenly cooled or, as it is usually stated, quenched, from above a transition point, the tendency is to retain to a large degree that phase present at the temperature from which it was cooled. In many cases, this phase is a solid solution and it is through the partial or complete decomposition of these solid solutions under well-controlled conditions that the striking variations in physical

properties are brought about. Steel, which is an iron-carbon alloy, furnishes the best example of this. Figure 78 is the equilibrium diagram of the iron, iron-carbide system. All types of carbon steels occur to the left of point *E* on this diagram. The carbon content of steels is usually less than 1.5 per cent.

All steels while cooling from the molten condition pass through the area *AGSE*. While in this area, they are composed completely

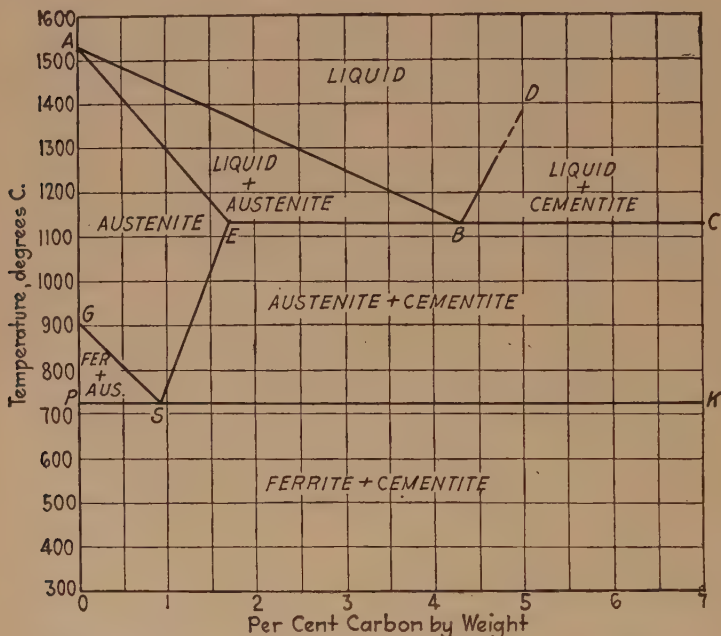


Fig. 78.—Equilibrium diagram of the iron, iron carbide system. ("The Science of Metals," Jeffries and Archer.)

of a solid solution of carbon in gamma iron. This solid solution is called austenite. Upon further slow cooling, each steel at some point crosses the broken line *GSE*. In the case of those which cross the portion *GS*, it is found that free alpha iron, called also alpha ferrite, is separating out. Alpha and gamma iron are allotropic forms of this metal, so it is clear that the transition point whose locus is *GS* is largely concerned with an allotropic change. Those steels which cross portion *SE* precipitate iron carbide usu-

ally called cementite. The crossing of the line *PSK* is attended by a complete change of the remaining solid solution, austenite, to a eutectoid mixture of alpha ferrite and cementite. In the final analysis, therefore, all slowly cooled carbon steels are an aggregate of alpha ferrite and cementite.

If a steel is heated to some point just above the line *GSE* and cooled very rapidly, the changes noted on slow cooling do not have time to occur completely. This results in the formation of constituents which can only be considered as intermediate steps in the change of the austenite to an aggregate of alpha ferrite and cementite. These intermediate products are the well-known martensite, troostite, and sorbite. Since their properties are markedly different from the normal aggregate of alpha ferrite and cementite, and they will retain these properties indefinitely, they are of very great importance to the steel treater. Their retention makes possible the widely varying combinations of hardness, tensile strength and ductility which are demanded in the industrial utilization of steel.

The importance to steel treaters of a knowledge of the position of the above-mentioned transition or critical points is evident; particularly since the points do not always occur at the same temperature, but show a certain hysteresis depending upon the rate of cooling or heating. The introduction of alloying elements also changes their position. In general, the effect of other elements is to lower the transition temperature in a similar way to the lowering of the melting point.

A somewhat similar situation exists in bronzes carrying from 13 to 28 per cent tin, as it is possible to increase their strength by quenching from above a certain transition point.

One of the most recent and interesting examples of improvement of physical properties by heat treatment is the work which has been done on duralumin and similar alloys. Duralumin is essentially an alloy of aluminum with about 3.5 to 4 per cent copper. The increase of strength is brought about by quenching the

alloy when in the condition of a solid solution and reheating for a definite time at temperatures from 100 to 180°C. One of the important things to know is the location of the line above which the alloy is completely a solid solution. Thermal analysis furnishes one of the most important means of determining the position of this line.

HEATING AND COOLING CURVES

Simple Time-temperature Curves.—If a substance is heated or cooled over a particular range and at a fairly constant rate, it is possible to take temperature readings at stated time intervals and plot a time-temperature curve which represents the rate of heating or cooling. If the temperature remains nearly constant at any time during the heating or cooling, there will be a sharp change in the slope of the curve, and a portion of the curve will be nearly parallel to the time axis. Figure 80 represents this condition. *BC* is that portion of the curve where the temperature remained constant. Such curves are typical of melting-point determinations and sharply defined constitutional changes. The halt in the cooling curve occurs because the evolution of heat on cooling through the transition point is sufficient to supply that radiated by the body, so that the temperature of the system remains constant for a definite interval. A similar time-temperature curve is obtained if heat is added at a uniform rate.

In an actual determination, the points *B* and *C* will not be as sharply defined as shown in the figure, and the flat portion of the curve may be very small. In some cases there may be a slight obliquity over the whole portion *BC*. In determining melting points, the heating curves show more obliquity than the cooling curves, and for this reason cooling curves are more generally employed.

Some molten metals, antimony, for instance, show a tendency to cool below the freezing point before solidification begins. This

phenomenon, known as supercooling or surfusion, is illustrated in Fig. 79.

If two metals are completely soluble in each other in all proportions in the liquid state, but nearly insoluble in the solid state, there is one proportion of the two which retains the liquid solubility to a lower temperature than any other proportion. This is called the eutectic alloy. When this alloy reaches the lowest temperature at which it is possible to retain liquid solubility, it

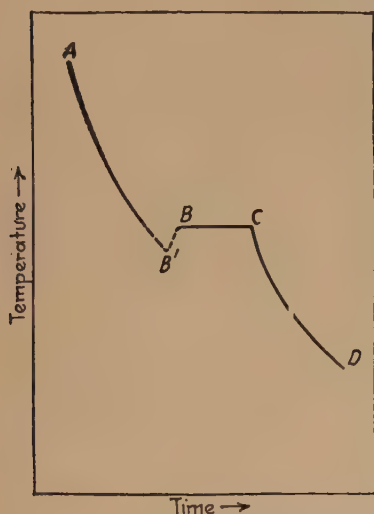


FIG. 79.—Cooling curve exhibiting supercooling. (*"The Science of Metals," Jeffries and Archer.*)

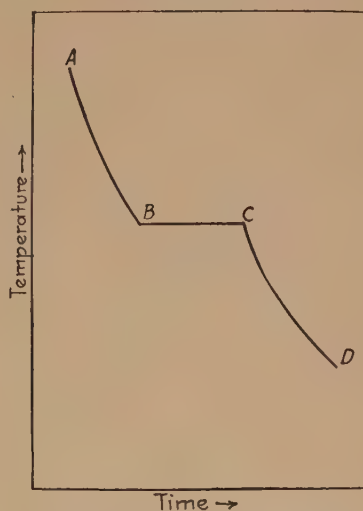


FIG. 80.—Cooling curve of a pure substance or a eutectic. (*"The Science of Metals," Jeffries and Archer.*)

decomposes into a physical mixture of the two metals. This physical mixture is called a eutectic. All such binary alloys tend on cooling to expel from solution the constituent which is present in excess of eutectic proportions, thereby allowing the remaining portion of the alloy to remain in liquid solution as long as possible.

The cooling curve of a pure eutectic has the same form as the curve of a pure metal (Fig. 80). If the alloy consists of a eutectic and an excess constituent, the cooling curve assumes the form shown in Fig. 81. The sloping portion *BC* represents the solidification of the excess constituent and the portion *CD* the solidification of the

eutectic. In this case the solidification of the alloy takes place over a temperature range represented by the vertical distance between *B* and *D*. The convexity of portion *BC* is due to the presence of two tendencies. The separation of the excess constituent tends to produce a halt in the curve, while the removal of the excess constituent from the liquid bath tends to lower the average melting point of the bath. The resultant of these two is the bulge in the curve.

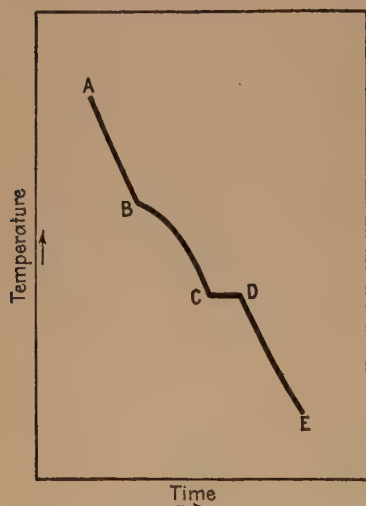


FIG. 81.—Cooling curve of a binary alloy consisting of an excess constituent and a eutectic.

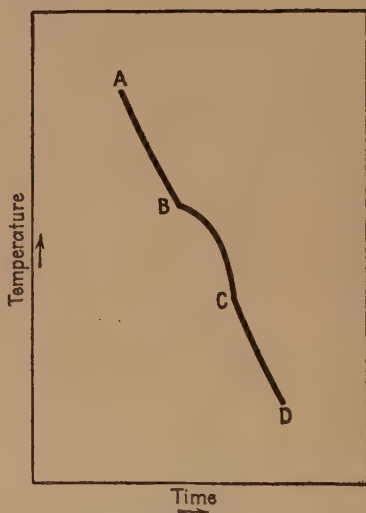


FIG. 82.—Cooling curve of a binary alloy consisting of one solid solution.

Figure 82 is the cooling curve of a binary alloy, the constituent metals of which are completely and mutually soluble in the liquid and solid states. Here again solidification takes place over a range *BC*. The convexity of the portion *BC* is also due to two tendencies. The metal with the higher melting point tends to solidify first, which would cause a halt in the curve. Since the metal with the lower melting point is soluble in the other, a small portion of the former is dissolved in the first crystals which are formed. The net result is the removal from the liquid of a greater amount of the metal with the higher melting point than that with

the lower melting point. The average melting point of the bath is therefore lowered, the actual curve being the resultant of the two tendencies.

The evolution of heat at some transition points is so slight that it would scarcely be noted on a simple time-temperature curve.

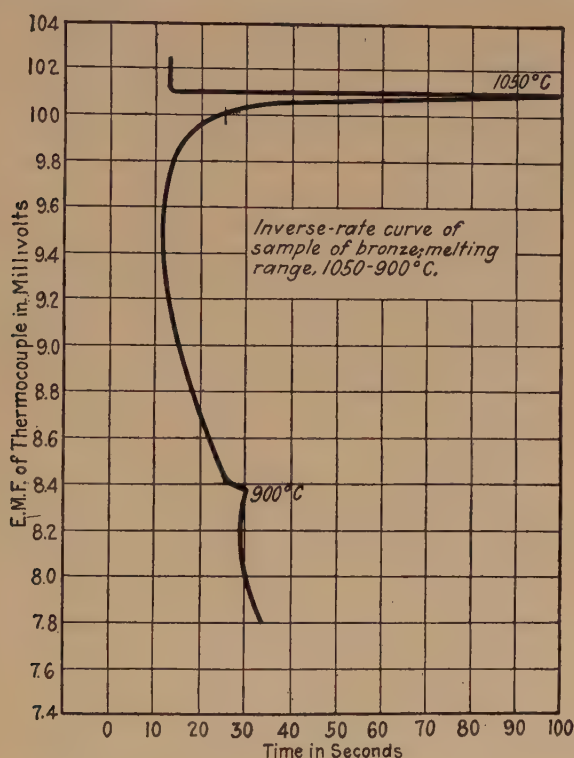


FIG. 83.—(U. S. Bur. Standards, T. P. 170.)

In order to make such transition points more prominent, the *inverse-rate* curve, the *differential* curve, or the *derived differential* curve may be used.

The Inverse-rate Curve.—The data for this curve is obtained by observing the time required for a specimen to fall through a pre-determined temperature interval. This temperature interval may be anything up to 10°C., depending on the accuracy required. The curve is obtained by plotting the time as an absolute value

against the lower temperature of each temperature interval. For instance, if it takes a specimen 20 seconds to drop from 560 to 558°C., the 20-second time interval is plotted against 558°C. The next 2°C. drop may require 30 seconds, which is plotted against 556°C. Merica¹ has suggested a simple means of determining these time intervals through the use of two stop watches. One is stopped and the other started at the end of each time interval. During each time interval, it is thus possible to record the length of the preceding interval.

Figure 83 is the inverse-rate curve of a bronze during solidification.

The Differential Curve.—This curve is obtained by observing the difference in temperature between the material under observation and a so-called neutral body having no transition points in the same temperature range, such as nickel or platinum, while the two are slowly heated or cooled. It is, of course, necessary that the two bodies be in very intimate contact during the operation. The arrangement of the system is illustrated in Fig. 84. Two thermocouples are employed, one a differential couple with a junction in each material and the other a carefully calibrated couple to indicate the temperature of the specimen under observation. By using a sensitive galvanometer with the differential couple, very small thermal variations may be detected. If the specific heats of the two materials are not widely different and they are in close contact, variations in the rate of heating or cooling make negligible errors. If there is a steady large deflection of the galvanometer, it may be convenient to reduce this to zero by a variable counter e.m.f. obtained by means of a battery and slide wire. The curve is obtained by plotting the temperature

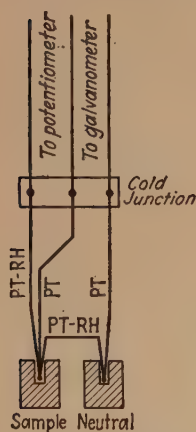


FIG. 84.—Diagram of arrangement for obtaining differential or derived differential curves. (U. S. Bur. Standards, T. P. 170.)

close contact, variations in the rate of heating or cooling make negligible errors. If there is a steady large deflection of the galvanometer, it may be convenient to reduce this to zero by a variable counter e.m.f. obtained by means of a battery and slide wire. The curve is obtained by plotting the temperature

¹ U. S. Bur. Standards, Sci. Paper 336.

difference between the sample and the neutral body against the temperature of the sample.

The Derived Differential Curve.—The apparatus required to obtain this curve is the same as for the differential curve. The only difference lies in the method of reporting and plotting the data. This method bears the same relationship to the differential curve as the inverse-rate curve bears to the simple time-temperature

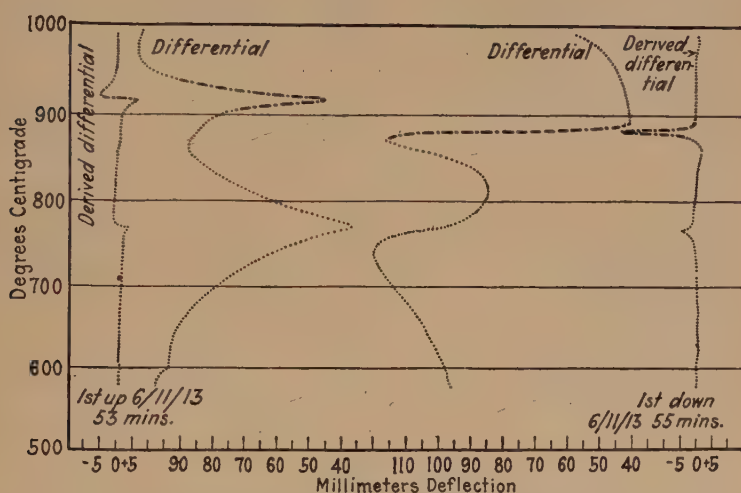


FIG. 85.—Differential and derived differential curves for a sample of pure iron. (U. S. Bur. Standards, T. P. 170.)

curve. For each predetermined temperature interval, say $2^{\circ}\text{C}.$, the difference in temperature between the two bodies is noted. In plotting a cooling curve this difference is plotted against the upper point of each temperature interval. In plotting a heating curve, on the other hand, it is plotted against the lower point of the interval. From a mathematical standpoint, this curve is the first derived curve of the differential curve with respect to the temperature. The advantage in its use lies in the fact that the transition points are more easily located. This is evident from Fig. 85, which represents the transition points in a piece of pure iron, as determined by both methods.

METHODS AND APPARATUS FOR THERMAL ANALYSIS

Resistance thermometer and thermoelectric and optical pyrometers are used in thermal analysis. The use of each type is determined by the temperature range, nature of the material under investigation, and other local conditions.

Melting-point Determinations.—The design of melting-point apparatus and the technique of operation are largely controlled by the properties of the material under investigation and the temperatures of melting. All of these points are very completely discussed in *Technologic Paper 170* of the U. S. Bureau of Standards from which the following figures and descriptions are taken. Only the more general types are here included. For special cases reference should be made to *Technologic Paper 170*, or other publications of the Bureau of Standards.

Figure 86 represents a melting-point furnace for precision work with metals and alloys melting below 1100°C .

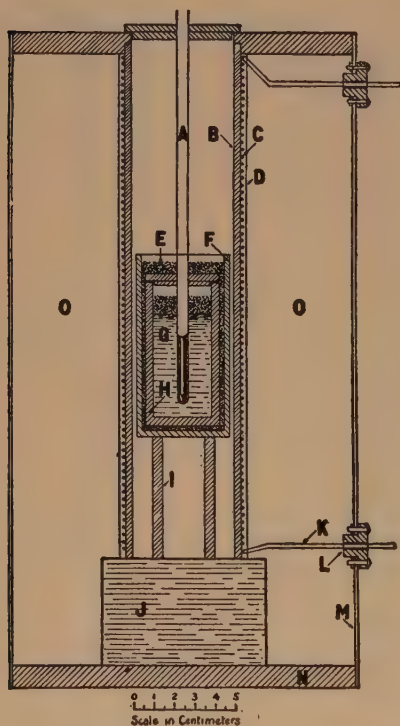


FIG. 86.—Electric furnace for melting point determinations. (U. S. Bur. Stand., T. P. 170.)

E. The porcelain crucible is supported by the alundum tube *I*. The heater tube is of alundum, R. A. 98; length, 25 centimeters; inside diameter, 5 centimeters; and wall thickness, 3 millimeters. This is preferably corrugated on the outside and is wound with 60 to 80 turns of No. 14 "chromel-A" wire *C* to the ends of which are welded the lead-in terminals *K* of No. 10 chromel. The alundum tubes *B* and *I* rest on a good non-conducting fire brick about 5 by 8

by 8 centimeters. The shell *M*, 32 centimeters high, is of sheet iron or monel metal painted with aluminum paint. The ends of the shell are closed by impregnated asbestos boards *N*, 1 centimeter thick and 17 centimeters in diameter. The annular space *O* is packed with silocel powder. The lead-in wires are insulated from the metal shell by asbestos board or steatite bushings. The furnace in series with a rheostat for control may be operated on 110 volts and consumes about 1 kilowatt at 1100°C.

General Precautions.—In order to melt for the first time a metal which is in small pieces, the graphite crucible, filled with the material, fitted with a cover having a hole in which the thermocouple fits tightly and surrounded by powdered graphite, is slowly heated. If convenient, *CO* or *N*₂ may be passed into the furnace, but *CO*₂ should not be used. The surface of the metal should not be covered with graphite at first, as it may filter into the interior and become imprisoned there. When the metal has been melted, however, the graphite layer on the surface is quite desirable. With the exception of antimony, which should be stirred just as the freezing point is reached to reduce supercooling, it is not advisable to stir the molten metals, as pockets of graphite are thereby formed.

In melting large crucibles of copper, care must be taken that the furnace is not burned out before the copper is melted. It is frequently desirable to use a thermocouple connected to the heating element attached to a temperature-control apparatus and arranged to prevent the winding being heated above 1200°C.

If there is doubt concerning the proper depth of immersion, several determinations should be made at different depths until a position is found where a slight variation does not affect the temperature measurement.

The pyrometer tube may be allowed to remain in the metal for a few degrees below the freezing point without breaking, and if it cannot be removed then, the metal should be immediately remelted.

A uniform rate of cooling of about 2°C. per minute from 10°C. above the melting point is satisfactory for a freezing-point determination. The values obtained from melting and freezing curves should agree to from 0.1 to 0.01° for pure metals, and the curves should have a flat portion extending over at least 10 minutes. If the curve is not fairly flat the metal is evidently impure, and hence possesses a melting range instead of a true melting point.

Technical Melting-point Determinations.—For ordinary technical testing, in which an accuracy of 5 to 10°C. is sufficient, the general procedure is the same as that discussed for precision work, except that less care is required in experimental details. It is not a wise practice to immerse a bare base-metal couple directly in a molten salt or metal. The couple should be protected by a metal or ceramic

tube, preferably of thin wall, in order to reduce heat conduction. For metals, Dixon graphite crucibles, which are less susceptible to oxidation than the Acheson graphite, or pure fire clay (except for aluminum) are satisfactory; while iron, calorized iron, nickel, nickel-chromium alloys, or duriron are serviceable for salts. For the checking of thermocouples pots of commercial tin, lead, zinc, sodium chloride, and copper of a fair degree of purity are sufficient. The melting points

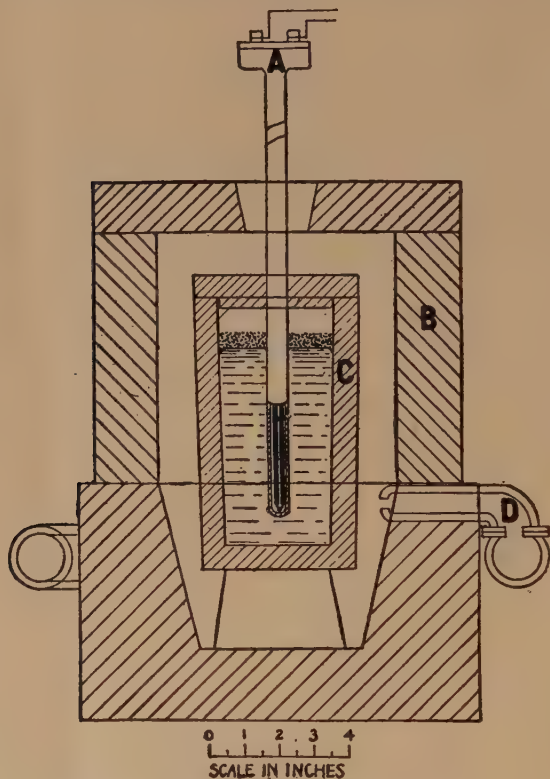


FIG. 87.—Gas melting furnace. (U. S. Bur. Standards, T. P. 170.)

of these materials will rarely differ from those of the pure substances by 10°C . and, if close checks are required, the melting points may be determined by means of an accurately calibrated couple. A gas furnace may be employed for heating, but the flame should not be allowed to strike the crucible on one side only. If the burner is directed along a radius of the furnace instead of tangential to its surface a baffle may be interposed before the crucible, or the crucible may be mounted on a pedestal above the flame. Under these circumstances it is desirable to protect the crucible by an outer metal tube. An excellent form of gas furnace is the melter's furnace illustrated in Fig. 87. The furnace is provided

with three burners *D*, only one of which appears in the drawing, mounted tangentially to the circumference in order to produce a spiraling flame. Excellent temperature uniformity is thus obtained.

Wire Method.—The wire method of determining melting points of metals consists in inserting at the hot junction of the couple a small length of wire drawn from the material to be investigated. Usually a rare-metal couple is employed. The couple is cut apart at the hot junction and the sample wire, preferably of about the same diameter as the wire of the couple and about 1 centimeter or less in length, is fused (not soldered) in. The couple is then mounted in a narrow tube, which may be closed at the lower end, and inserted into a uniformly heated furnace, as illustrated by Fig. 88. The temperature of the furnace is increased very slowly as the melting point is approached, and the e.m.f. of the couple is observed when it comes to a halt during melting. This occurs slightly in advance of the instant that the circuit is broken by the melting. The temperature corresponding to this e.m.f. on the calibration curve of the couple is the desired melting point. The introduction of the short piece of metal produces no effect on the thermoelectric circuit, provided it is at a uniform temperature. The two metals most satisfactorily employed with this method are gold and palladium, although many other metals could be used with the proper atmosphere. The experimental manipulation for palladium is a little difficult. A platinum-wound furnace must be used, and the two insulating tubes of the couple must not come into contact with each other or with the furnace walls; otherwise electrical leakage occurs. A leak between the wires of the couple produces a peculiar effect at the instant of melting of the palladium. Instead of the galvanometer showing zero deflection, it will indicate the very large voltaic e.m.f. developed when the porcelain acts as an electrolyte, since the metallic shunt of low resistance across this e.m.f. is broken when the palladium melts. With proper care results by this method are reproducible to 1°C . It is frequently convenient to sight a microscope of low power on the loop of wire and observe the melting. If the rate of heating is slow, sufficient time elapses from the incipient melting to secure several reliable potentiometric readings before the circuit is broken.

The wire method is occasionally employed for copper heated in air. The temperature so obtained, however, is not reliable. It may be any value from 1063 to 1083°C . depending upon the rate of heating, and hence upon the amount

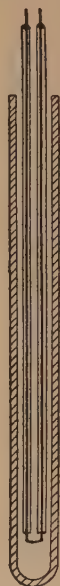


FIG. 88.—Apparatus for wire method. (*U. S. Bur. Stand., T. P. 170.*)

of oxide formed. With very slow heating the wire may be converted into CuO_2 , which melts at about 1190°C .

Metals and Alloys.—Above 1400°C . the difficulties involved in the use of thermocouples for melting-point determinations are very great. Refractory tubes are attacked by the metals and are permeable to gases which contaminate the couple. The calibration of the couple changes, inhomogeneity develops, and troubles arise from electrical leakage. For these reasons the use of optical pyrometers is desirable and, above 1550°C ., necessary. The disappearing-filament

type of optical pyrometer is most satisfactory, since it is capable of high precision and requires a very small source upon which to sight. Special care must be given in the use of optical pyrometers to insure that black-body conditions are closely approximated.

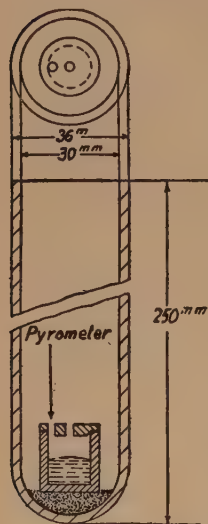


FIG. 89.—Apparatus for melting points of metals and alloys with optical pyrometer. (U. S. Bur. Stand., T.P. 170.)

For metals and alloys melting below 1750°C . the experimental device shown in Fig. 89 is suitable. The outer tube is made of sillimanite porcelain, melting at 1810°C . and constitutes the unit to be inserted into a furnace. The crucible inside this tube is about 18 millimeters in diameter and 20 millimeters high, and is provided with a cover having two holes, 2 to 3 millimeters in diameter, in the positions illustrated. The pyrometer is focused on the outer hole and the central hole is for observing the progress of freezing or melting. If the metal in the crucible is molten the central hole appears quite dark against a brighter background because the level metal surface reflects the image of the upper and cold part of the furnace. The surface under the side hole, however, is convex on account of the surface tension of the metal, and the V-shaped depression formed

between the metal and the side wall affords a satisfactory black body upon which to sight the pyrometer. The outer tube should be uniformly heated for a distance at least twice its diameter, and the short crucible should be filled about half full with metal. Tall crucibles are not desirable, as they are less likely to be uniformly heated, and any non-uniformity disturbs the black-body conditions. Although it is realized that such a system is not ideal for producing black-body radiation, especially when the temperature is continually changing, as is necessary in melting-point determinations, still it may be concluded on the basis of many careful observations that the error, in general, does not amount to more than 2 or 3°C . For more precise work it is possible to fix to the cover of the crucible a reentrant tube immersed directly in the metal, and into which the

pyrometer is sighted. This method is frequently employed for the standardization of an optical pyrometer by direct melting-point determinations.

Crucibles and Protecting Tubes.—Of all crucible materials Acheson graphite has the greatest utility. It is very pure, can be machined into any desired shape, and is not attacked by most of the common metals. At high temperatures the gases formed from its oxidation provide the reducing atmosphere necessary for the protection of the metal.

Some metals, such as nickel and iron, combine with graphite, and certain other metals also should not be heated under the reducing conditions present with graphite. Crucibles of magnesia alumina, or mixtures of the two, are suitable for iron and nickel. Porcelain crucibles may be used for many of the metals, but there is always danger of these cracking when the metal melts or freezes.

Up to 500°C. protection tubes and insulating tubes for the couple, made of pyrex glass, are useful. From 500 to 1100°C. lower-grade porcelain, glazed on the outside only, or fused quartz, are satisfactory. Above 1100°C. tubes having a composition approximating that of sillimanite, Al_2O_3 , SiO_2 , are recommended.¹ Porcelain tubes, or crucibles, or any material containing silica, cannot be used in contact with aluminum, as the silica is readily attacked. Aluminum may be melted in a graphite crucible, and the porcelain protecting tube may be itself protected by a very thin sheath of graphite. At present there is no satisfactory protecting tube for nickel. This material and its alloys may be best studied by optical methods.

Inorganic Salts and Silicates.—On account of the low heat diffusivity and latent heat of fusion of salts and silicates, considerable difficulty is encountered because of the obliquity of the melting or freezing curves. Consequently, it is necessary to use tall, narrow charges and slow rates of heating. Few salts can be heated in a reducing atmosphere and hence graphite crucibles are prohibited. Porcelain and fire clay are attacked by most salts, so that metal crucibles must be employed. Of these, platinum, platinum alloys, and nickel have the widest utility. The thermocouple protecting tube of porcelain must be itself protected by a thin metal sheath. In many cases salts do not attack platinum perceptibly, so that the thermocouple may be immersed directly in the molten salt. When this is done the crucible must be free from volatile metals, such as iridium, especially for work at high temperatures; otherwise the couple will become contaminated. If no protecting tube is employed, very small crucibles may be used, from 1 to 2 centimeters in diameter and 2 to 4 centimeters high. If the salt is quite volatile and the vapors distill into the furnace, an additional protection tube for the furnace heater is necessary. The melting or freezing points of the

¹ Such porcelain is known as Usalite or Impervite.

nitrates, chlorides, and sulphates of the alkali and alkali earth metals may be determined in the above-described manner.

The apparatus used by the Geophysical Laboratory for silicate work is shown in Fig. 90. The marquardt or sillimanite porcelain tube *A* is joined to a platinum sleeve *B*, 5 by 1.2 centimeters, into which tightly fits the platinum crucible *C*, containing the charge. The platinum thermocouple, carefully centered, is inserted with no protection. Great care must be taken to avoid the presence of impurities, such as chips of porcelain from the tube *A*, etc., as the lowering of the freezing point by impurities is proportional to the square of the absolute temperature and becomes very serious at high temperatures.



FIG. 90.—Silicate melting point apparatus. (U. S. Bur. Stand., T. P. 170.)

If it seems advisable to use the resistance thermometer for melting-point determinations, reference should be made to *Scientific Paper* 124 of the Bureau of Standards.

Transition Points in Solid Substances.—It is possible to determine the location of transition points in solids by means of the same apparatus as has been described for melting-point determinations. In most cases, however, the amount of heat which is absorbed or evolved is so small that the halts in the curve are liable to be obscured by variations in heating and cooling rates or by radiation or convection losses. For this reason more refined types of apparatus have been devised for this type of thermal analysis. A few of the more important ones will be described.

Modified Rosenhain Furnace.—Rosenhain¹ devised a furnace for thermal analysis, particularly of metals, whereby the sample was slowly raised and lowered through a vertical furnace which was heated at the upper end only. Curves were plotted by the inverse-rate method. In his original paper Rosenhain pointed out some difficulties and made suggestions for their elimination. Scott and Freeman,² following Rosenhain's suggestions and

¹ *Jour. Inst. Metals*, vol. 13, p. 160, 1915.

² *U. S. Bur. Standards, Sci. Paper* 348.

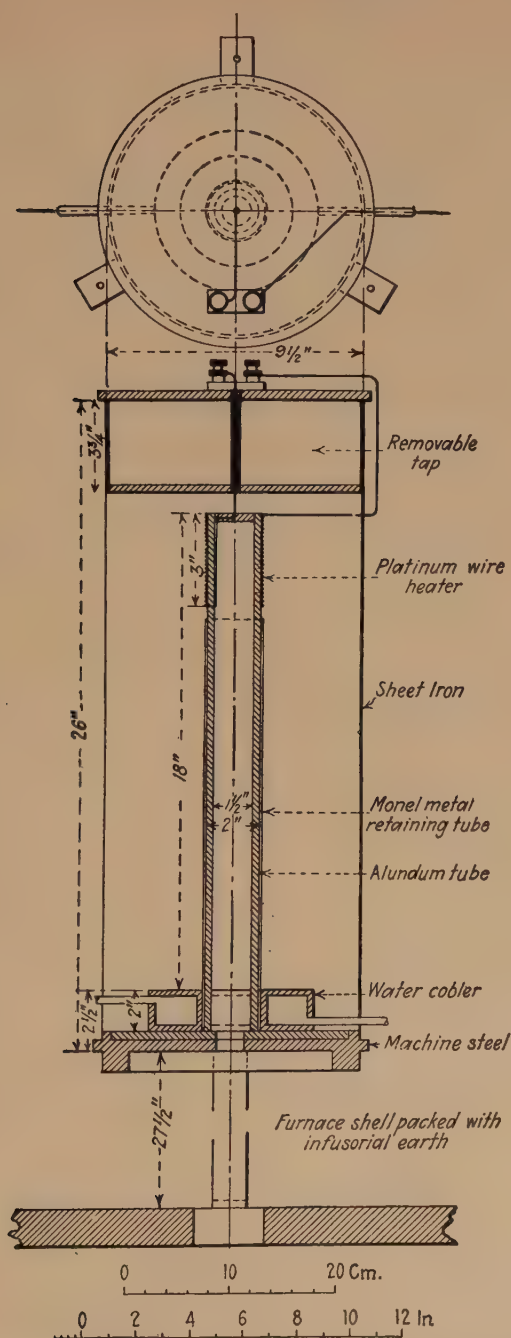


Fig. 91.—Diagram of furnace used in modified Rosenhain apparatus for thermal analysis, (U. S. Bur. Stand. S. P. #348.)

adding some improvements of their own, have devised a successful modification of this furnace.

Figure 91 is a diagram of the furnace. It stands in a vertical position with its lower end 27.5 inches above the surface of the supporting table. The upper end is closed while the lower end is open to allow the gradual elevation of the sample from the cold to the hot portion of the furnace. The hot junction of a platinum, platinum-rhodium thermocouple is held tightly by a saw cut in the sample. The sample is therefore supported by the porcelain tube through which the thermocouple wires are threaded. Sample and couple are inserted into a quartz tube which is supported by a brass plug at the bottom. This plug is drilled in such a way that the quartz tube can be evacuated. This whole assembly is placed on the elevating mechanism in such a way that it can be slowly raised or lowered through the furnace.

Figure 92 is a diagram of the elevating mechanism. The quartz tube is held in a vertical position by the tube holder *D* and the clamps *E*. The elevator is raised by means of weights *K*, the rate of elevation being controlled by the flow of oil through the graduated needle valve *M*. When the elevator has reached its highest point, weights *K* are removed and weight *J* is placed on the elevator to lower it. The rate of lowering is also controlled by the flow of the oil in the opposite direction through the needle valve *M*.

It is possible to use the differential method with this furnace, but Scott and Freeman report that more satisfactory results are obtained by the inverse-rate method. Temperature readings are best made by means of a deflection potentiometer.

Leeds and Northrup Apparatus.—This apparatus uses the differential method. The neutral body is a cylinder of nickel drilled in such a way that the sample under investigation can be inserted until its end is nearly flush with the end of the neutral body. The sample has in the end which is inserted in the furnace a No. 10 hole $\frac{1}{2}$ inch in length. The differential couple and the couple for measuring the temperature of the sample are threaded

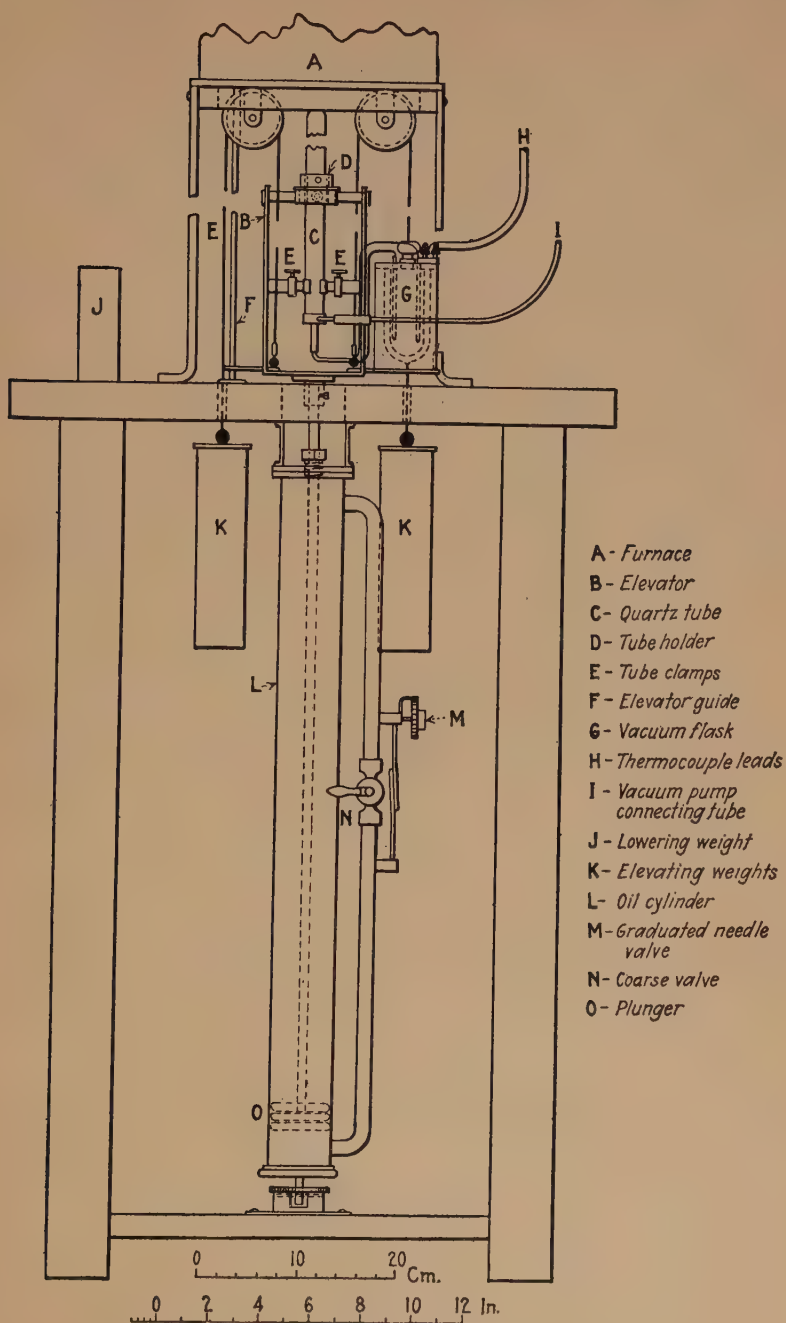


FIG. 92.—Diagram of elevating mechanism used in modified Rosenhain apparatus for thermal analysis. (U. S. Bur. Stand., S. P. #348.)

through a four-hole porcelain tube. This tube carrying the couples is inserted through the open end of the nickel cylinder to such a distance that the hot junction of the temperature measuring couple is within the sample and the differential couple has one junction in the sample and the other further back where it is wholly surrounded

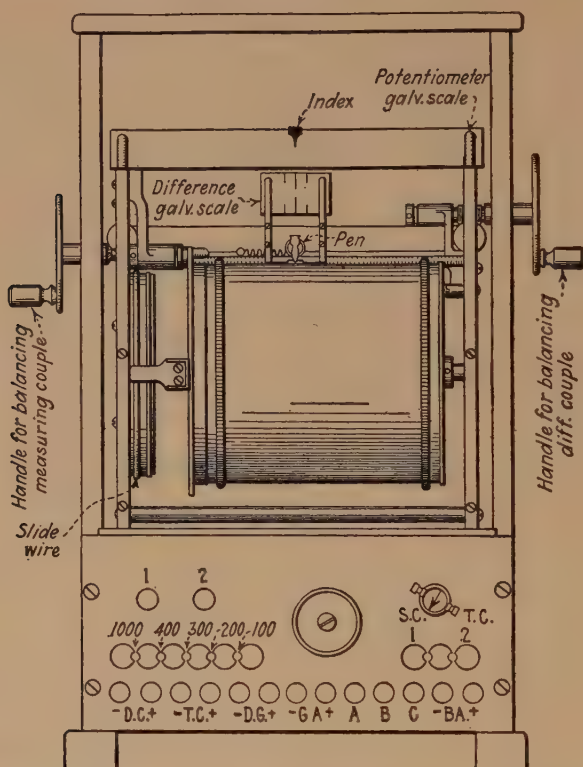


FIG. 93.—Leeds and Northrup apparatus for thermal analysis. (Leeds and Northrup Co.)

by the nickel. This whole assembly is placed in a cylindrical electric resistance furnace, the temperature of which can be rapidly raised or lowered. Cold-junction errors are automatically compensated.

Figure 93 is a diagram of the apparatus by means of which the differential curve is drawn. The measurement of the temperature of the sample is made by means of a simple null-point

potentiometer, the slide wire of which encircles the drum. The galvanometer is suspended about 1 meter back of the instrument and a ray of light from a lamp fastened to the back of the instrument is reflected from the galvanometer mirror to the upper frosted scale as indicated. The paper upon which the curve is drawn fits around the cylindrical surface of the drum, just covering it. This paper is graduated in millivolts and temperature, and must be placed on the drum in such a way that its lowest millivoltage figure registers with the corresponding figure on the drum. The paper is held on the drum by two helical springs which encircle the drum. The circuit having been checked against the standard cell, the temperature of the sample is obtained by revolving the drum by means of the crank on the left side of the instrument box, until the beam from the galvanometer is brought to the point marked "index". As the temperature of the sample increases this balance is maintained by slowly turning the drum.

If the pen carriage remains stationary as the temperature of the sample increases, a straight line will be drawn on the paper as the drum revolves. The pen carriage, however, may be moved back and forth in a direction perpendicular to that of the drum surface by the crank on the right side of the instrument. These movements are controlled by the difference in temperature between the neutral body and the sample.

The lead wires from the differential couple are connected to a second galvanometer which is suspended beside the potentiometer galvanometer. The beam from this galvanometer is directed upon the frosted scale which is fastened to the pen carriage. As long as there is no difference in temperature between the sample and the neutral body, the beam from the differential galvanometer will remain stationary. As soon as a transition point is reached, however, the rates of heating or cooling of the sample and the neutral body cease to be the same and a small temperature difference appears. This causes the beam from the differential galvanometer to move either to the right or the left. In order, then, to keep the

beam in the same position on the differential galvanometer scale it is necessary to move the pen carriage a corresponding distance. The curve being drawn on the drum then shows a break at the temperature at which the transition point occurs.

In series with the differential galvanometer is a variable resistance which makes it possible to decrease the sensitivity of the galvanometer. Otherwise the beam may swing outside of the instrument in case the transition point is accompanied by the evolution or absorption of a large amount of heat. On the other hand, the sensitivity of this apparatus is not great enough to locate transition points, the thermal variation of which is small. The curve can be replotted as a derived differential curve, thus bringing out more strongly points which may be doubtful.

Brown Transition-point Recorder.—This instrument is an application of the millivoltmeter type of e.m.f. recorder to the determination of transition points by the differential method. The galvanometer has two low-resistance coils and one high-resistance coil. One of the low-resistance coils is connected permanently in series with the high-resistance coil and the temperature measuring couple. When this circuit alone is connected, the record made on the chart is the temperature of the sample. At alternate intervals the second low-resistance coil, which is in series with the differential couple, is connected into the circuit. This causes the galvanometer needle to swing to a lower position on the chart. As a result of the operations just described, two curves will be plotted. If there is no e.m.f. in the differential circuit, the corresponding points on the two curves will always be practically the same distance apart. As soon as any e.m.f. is present in the differential circuit, the distance between the two curves shows a fairly sharp increase or decrease, thus locating the transition point. The sensitivity of this instrument is only sufficient for the most strongly marked transition points. Base-metal couples are used.

The Heat Treatment of Steel.—At an earlier point in the present chapter it was pointed out that the useful variations possible in the

properties of steel by means of heat treatment were due to the presence of transition or critical points in the steel. To harden steel it is necessary to quench it from above the critical point. The location of this critical point must be known for every steel. Two methods have been devised for indicating by attendant physical phenomena that steel parts being heat treated have actually passed through the critical range.

The Hump Method.—This method, devised by Leeds and Northrup, makes use of the fact that as heat is added at the transition point no change in temperature occurs. The steel is placed in a specially designed electric furnace in such a way that it is in close proximity to and surrounds the thermocouple. The e.m.f. of the thermocouple is shown on a specially designed potentiometer recorder. As the furnace heats up the temperature indicated on the recorder increases at a uniform rate. As soon as the critical point is reached, the steel absorbs a large amount of heat without increase of temperature. This produces a “hump” in the heating curve and indicates to the operator that the steel has been heated to the critical point. As soon as the rate of heating becomes constant again, it is time to remove the steel from the furnace and quench it. The distance past the hump to which it is necessary to carry the charge is dependent upon the size and shape of the charge. A certain amount of experience is necessary for successful operation.

The Dilatometric Method.—It has been observed that as steel is heated through its critical range a contraction in volume occurs, as well as an absorption of heat. If, therefore, while the steel is being heated, it is placed in rigid contact with an indicator such as an Ames dial, it will be noted that the metal expands at a uniform rate until the critical range is reached. While passing through the critical range the dial will remain stationary, or may even indicate a contraction. After the range is passed the dial again indicates a uniform expansion. With some experience, it is possible to determine the best time to quench the steel after the point of contraction has been passed. This method which has been used only recently

is quite fully explained in a paper and discussion by Harder, Dowdell, and Forsythe.¹

EXPERIMENT 1

Melting Point of Zinc

Using a furnace similar to the one shown in Fig. 86, determine the melting and the freezing points of a sample of pure zinc. If the crucible contains a mass of solid metal, close the heating circuit until the metal is molten. Cover the surface with graphite powder, insert the thermocouple tube, and start the determination. If a charge of small pieces of solid metal is being melted, the procedure is the same. Best results will be obtained by starting to cool from a point about 10°C. above the melting point. The rate of cooling should be about 2°C. per minute. As soon as the metal is solid, turn on the heating current and obtain the data for a melting-point curve.

a. Plot simple time-temperature curves of the freezing and melting point, taking temperature readings every 20 seconds with some type of potentiometer.

b. Repeat the determination, plotting inverse-rate curves for the freezing and melting points. The data for these curves is obtained by determining the time interval in seconds for each 2°C. fall or rise of temperature.

EXPERIMENT 2

The Transition Points of Iron and Steel

Make determinations of the critical points (on both heating and cooling) of the following samples, plotting inverse-rate curves:

1. Pure iron.
2. 0.06 per cent carbon steel.
3. 3.5 per cent nickel steel with 0.2 per cent carbon.

The determinations may be made by means of a modified Rosenhain furnace, or a Leeds and Northrup transformation point apparatus. Detailed directions for the operation of this latter apparatus are supplied by the company.

NOTE.—If no apparatus of any type is available, it is possible to carry out this experiment in a furnace of the type shown in Fig. 86.

¹*Trans. Am. Soc. Steel Treating*, vol. 9, p. 403, 1926.

CHAPTER IX

REFRACTORY MATERIALS USED IN PYROMETRY

Since the subject of pyrometry deals almost exclusively with the measurement of high temperatures, it is greatly concerned with the properties of refractory materials. Fluid and resistance thermometers require bulbs which will not be affected by the temperature ranges over which they operate. Thermocouples require protecting tubes which will not fuse, contaminate the wires, or react chemically with the surrounding medium. There is also the question of crucibles and furnace materials for the calibration of pyrometers. It is from these viewpoints that the subject of refractory materials will be dealt with in the present chapter.

Fluid-thermometer Bulbs.—Practically all mercurial thermometers employ glass containers, although some manufacturers have used fused quartz as containers for the mercury, especially when the upper range is high. The results obtained with quartz thermometer bulbs have not been of such a quality as to warrant their extensive use at low temperatures, although it is imperative to use them at temperatures as high as 750°C . At this temperature hard glass softens. The limit for the ordinary mercury in glass thermometers is about 550°C . In certain types of industrial thermometers the bulb is enclosed in a metal tube to furnish protection from bending or swelling. Any metal melting above 600°C . may be used for this purpose, depending upon the type of service. There is, of course, considerable lag in the readings of such instruments although this may be greatly reduced by filling the space between the bulb and the metal protecting tube with a conducting medium. Mercury is used below 200°C . and heavy oils in the higher range. Pressure thermometers use metal bulbs largely. Here again the metal must be chosen which is best suited to con-

ditions. It must not react with the material, the temperature of which is being taken, nor with the fluid contained within it.

Resistance-thermometer Bulbs.—As has been brought out in the discussion of resistance thermometers, spirals of platinum or nickel wire are used as resistor units. Iridium, palladium, and rhodium have been suggested as resistor materials, but are not used to any appreciable extent. The resistor wire is wound around plates or tubes of such materials as mica, steatite, or quartz. The spiral thus mounted is placed within a tube of glazed porcelain which in turn is protected by an outer metal of either iron or nickel. Other metals may be used as necessary. Since the range of resistance thermometers is rather low, the refractory aspect of the mounting is not of as much importance as in the case of thermocouples. It is very essential, however, that the mounting be impervious to any material into which the bulb may be introduced.

Protection of Thermocouple Elements.—The mountings of thermocouples are made with two ideas in mind. First, the two elements of the couple must be insulated from each other; and, second, they must be protected from the possible effects of the medium into which the couple is introduced. The usual mounting consists of two parts, an inner tube with longitudinal holes through which the couple wires may be threaded, and an outer or protection tube proper into which the longitudinally bored tube carrying the wires is inserted. In the case of base-metal thermocouples, using wire of large diameter, the outer tube is sometimes omitted. The insulating tubes, however, must always be used. These insulating tubes must be made of refractory materials which will not fuse at any temperature to which the couple may be heated.

Platinum, platinum-rhodium couples are particularly sensitive to reducing conditions. If exposed to the action of carbon monoxide for any length of time a carbide of platinum is formed and the wires become very brittle and soon fracture. While not so susceptible to oxidizing conditions, it is very necessary that they never be used without adequate protection tubes. Iron-constantan

couples are very sensitive to oxidizing conditions, particularly the iron element and must, therefore, be kept in a neutral or slightly reducing atmosphere. The same is true of copper-constantan couples, if used at temperatures above 300°C. In the lower ranges they need no protection.

It is sometimes necessary to use a secondary tube surrounding the primary gastight protecting tube. The secondary tube is used to give added strength to the assembly, to protect the outer glazed surface of the primary tube from abrasion or fluxing action, and to prevent bending of the primary tube due to softening at high temperatures. Secondary tubes are made of metals or unglazed refractory materials. As summarized in *Technologic Paper* 170 of the U. S. Bureau of Standards an ideal primary protecting tube should fulfil as nearly as possible the following conditions. The importance of individual members of this list of conditions would vary with the process in connection with which the couples were to be used:

1. Low porosity of gases. Many tubes become very porous to furnace gases at high temperatures. Furnace gases usually attack the couple.

2. Low volatility. Certain metal tubes are undesirable at high temperatures because the metal distills upon the couple, thus altering its calibration.

3. Ability to withstand high temperature.

4. Ability to withstand sudden changes in temperature.

5. Ability to withstand mechanical shocks and strains.

6. High rigidity or viscosity. Protecting tubes frequently deform and exhibit the phenomenon of plastic flow at high temperatures.

7. Thermal conductivity. High thermal conductivity is frequently desirable when rapidly changing temperatures are measured. Usually, however, low thermal conductivity is desired so that the flow of heat along the tubes is as small as possible.

8. Ability to resist corrosion from molten metals or furnace gases. No protecting tube has been developed which fulfils all these conditions perfectly, but a good many have been developed which give excellent service for special purposes.

Table IX gives in a condensed form information regarding types of refractory materials as applied to thermocouple protecting tubes.

TABLE IX

Material	Chemical constitution	Applications	Temperature range	Advantages and limitations
Iron and steel.....	Alloys of iron and carbon	Primary tubes	Up to 850°C.	Oxidize easily. Are inexpensive and quite satisfactory for base-metal couples
Calorized iron.....	Wrought iron with surface coating of aluminum	Primary and secondary tubes	Up to 850°C.	Resists oxidation better than uncoated iron or steel
Duriron.....	High-silicon cast iron	Primary and secondary tubes	Up to 900°C.	May fracture with sudden temperature changes. Excellent protection against acid fumes
Fused quartz.....	SiO ₂	Insulating, primary, and secondary tubes	Up to 1050°C.	Should not be used with noble-metal or chromel-alumel couples. Resists oxidation. Practically impervious except to reducing gases. Low temperature coefficient. Resists acid fumes
Chromel, nichrome...	Alloys of nickel and chromium	Primary and secondary tubes	Up to 1100°C.	High mechanical strength. Low porosity. Good resistance to oxidation. Are more expensive than iron and steel but life is longer. Must be used in cast condition
Chromon.....	Alloy of iron, 75 per cent, and chromium, 25 per cent)	Primary and secondary tubes	Up to 1100°C.	May be used for short periods to protect thermocouples from the action of molten brass and bronze
Alundum.....	Fused Al ₂ O ₃ with clay binder	Insulating, primary, and secondary tubes. Especially good for secondary tubes	Up to 1400°C.	Is somewhat porous. May be glazed, but glaze lowers fusion point. Very good for use with noble-metal thermocouples
Nickel.....	Nickel	Primary and secondary tubes	Up to 1400°C.	Resists oxidizing conditions

TABLE IX.—(Continued)

Material	Chemical constitution	Applications	Temperature range	Advantages and limitations
Porcelain: Marquardt, usalite, and impervite....	Very pure clays	Insulating and primary tubes	Up to 1500°C.	Must be glazed to be impervious to gases. Excellent for noble- metal couples. Less pure porcelain tubes may be used up to 1200°C. Porcelain tubes must not be subjected to sudden temperature changes
Carborundum.....	SiC	Secondary tubes	Up to 1500°C.	High mechanical strength. Should not be used at high temperatures as a protecting tube for unvitrified glazed porcelain. Upper end of tube should have ready access to air
Corundite.....	Emery with clay binder	Secondary tubes	Up to 1500°C.	
Fire clay.....	Al ₂ O ₃ -SiO ₂	Insulating and secondary tubes	1400°C.-1750°C. depending on purity of clay	Secondary protection tubes in kilns, glass, and steel furnaces. Insulating tubes for base-metal thermo- couples
Graphite.....	Carbon	Secondary tubes	Up to 3000°C.	May be used in mol- ten metals. Noble- metal couples must be protected from its action
Mullite.....	3Al ₂ O ₃ .2SiO ₂	Primary tubes	Up to 1800°C.	Has not been widely used. Apparently a most excellent all- around refractory
Zirconium, oxide, and Baddeleyite	ZrO ₂		Up to 2700°C.	Has not been widely applied to pyro- metric service as yet. An excellent refrac- tory

Crucibles and Furnace Tubes.—Crucibles for the determination of melting points or the standardization of thermocouples by means of molten metals are best when made of graphite. If the standard sizes of commercial crucibles are not suitable, it is possible to obtain bars of graphite and to machine out crucibles of almost any

desired depth and diameter. Graphite crucibles must be protected against strongly oxidizing conditions.

For the ordinary calibration of thermocouples by comparison with a standard couple, tubular electric furnaces are most desirable. It has been the authors' experience that alundum tubes are most satisfactory for this service. These can be obtained in a variety of lengths and diameters.

APPENDIX

I. APPLICATIONS OF PYROMETRY

The following tabulation presents in brief form some of the uses of pyrometers and the particular kinds of pyrometers which are best adapted to each type of service:

SERVICE	PYROMETERS USED
Anchor ice formation near power plants.....	Resistance thermometers
Iron blast furnace:	
Molten iron.....	Optical pyrometers
Molten slag.....	Optical pyrometers
Tuyère temperatures.....	Optical pyrometers
Hot blast.....	Base-metal thermocouples
Top gases.....	Base-metal thermocouples
Bakeries.....	Fluid thermometers Bimetallic thermometers Resistance thermometers Base-metal thermocouples
Boilers:	
Combustion space.....	Optical pyrometers
Economizers	
Feed-water heaters	
Stack gases	Fluid thermometers and base-metal thermocouples
Core ovens.....	Recording fluid or bimetallic thermometers Base metal thermocouples
Ceramic industries:	
Drying kilns.....	Fluid thermometers
Burning kilns.....	Base- and noble-metal thermocouples
Freight cars (refrigerating).....	Resistance thermometers
Freight steamers (cargo temperatures).....	Resistance thermometers
Galvanizing kettles.....	Base-metal thermocouples
Glass manufacture:	
Melting furnace.....	Optical and radiation pyrometers Partially immersed noble-metal thermocouples
Annealing ovens.....	Fluid thermometers Base-metal thermocouples
Incandescent lamp filaments.....	Optical pyrometers of disappearing-filament type
Incandescent gas mantles.....	Modified radiation pyrometer
Lumber drying.....	Resistance thermometers
Malleable-iron manufacture:	
Air furnace.....	Optical pyrometers
Annealing ovens.....	Base-metal thermocouples

SERVICE	PYROMETERS USED
Oil refineries.....	{ Fluid thermometers Base-metal thermocouples
Portland-cement kilns.....	
Steel:	Optical pyrometers
<i>Manufacture:</i>	
Molten metal as it emerges from furnace or ladle.....	Optical pyrometers
Ingots and forgings.....	Optical and radiation pyrometers
<i>Heat Treatment:</i>	
Hardening furnaces for ordinary forgings	Base-metal thermocouples
Hardening furnaces for tool steel.....	Base-metal thermocouples
Hardening furnaces for high-speed steel	Noble-metal thermocouples
Oil baths for tempering.....	{ Fluid thermometers Base-metal thermocouples
Cyanide pots.....	
Lead pots.....	Base-metal thermocouples

II. TABLE OF BOILING POINTS ARRANGED IN NUMERICAL ORDER

(Many of these may be used in standardization of pyrometers)

Helium.....	— 268.9°C.
Hydrogen.....	— 252.7°C.
Nitrogen.....	— 195.8°C.
Oxygen.....	— 183.0°C.
Carbon dioxide (CO ₂).....	— 78.5°C.
Ammonia (NH ₃).....	— 33.4°C.
Carbon disulphide.....	+ 46.3°C.
Carbon tetrachloride.....	76.8°C.
Water.....	100.0°C.
Naphthalene.....	217.9°C.
Mercury.....	356.9°C.
Sulphur.....	444.5°C.
Selenium.....	688.0°C.
Cadmium.....	767.0°C.
Zinc.....	907.0°C.
Magnesium.....	1115.0°C.
Bismuth.....	1450.0°C.
Lead.....	1620.0°C.
Aluminum.....	1800.0°C.
Manganese.....	1900.0°C.
Silver.....	1950.0°C.
Tin.....	2260.0°C.
Copper.....	2300.0°C.
Gold.....	2600.0°C. ?
Nickel.....	2900.0°C. ?
Molybdenum.....	3700.0°C. ?

III. TABLE OF MELTING POINTS ARRANGED IN NUMERICAL ORDER
(Many of these may be used in standardization of pyrometers)

Helium.....	Below — 272.2°C.
Hydrogen.....	— 259.1°C.
Oxygen.....	— 218.4°C.
Nitrogen.....	— 209.8°C.
Chlorine.....	— 101.6°C. ?
Mercury.....	— 38.8°C.
Water.....	0.0
Naphthalene.....	80.1°C.
Cupric nitrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$).....	114.5°C.
Tin.....	231.8°C.
Bismuth.....	271.0°C.
Cadmium.....	320.9°C.
Lead.....	327.5°C.
Zinc.....	419.4°C.
Lead chloride (PbCl_2).....	501.0°C.
Antimony.....	630.5°C.
Magnesium.....	651.0°C.
Aluminum.....	660.0°C.
Calcium chloride (anhydrous) (CaCl_2).....	772.0°C.
Sodium chloride (NaCl).....	801.0°C.
Silver.....	960.5°C.
Gold.....	1063.0°C.
Copper.....	1083.0°C.
Lead sulphide (PbS).....	1114.0°C.
Barium fluoride (BaF_2).....	1280.0°C.
Calcium fluoride (CaF_2).....	1360.0°C.
Nickel.....	1452.0°C.
Iron.....	1535.0°C.
Palladium.....	1553.0°C.
Platinum.....	1755.0°C.
Molybdenum.....	2620.0°C.
Tantalum.....	2850.0°C.
Tungsten.....	3370.0°C.
Carbon.....	3600.0°C. ?

IV. MELTING POINTS OF SOME REFRACTORY MATERIALS

Coal ash.....	1100–1500°C.
Fire clay.....	1400–1750°C.
Silica.....	1700–1750°C.
Bauxite.....	1600–1800°C.
Kaolin.....	1740°C.
Chromite.....	1990–2180°C.
Alundum.....	2050°C.
Magnesia.....	2150–2800°C.
Carborundum.....	Above 2700°C.
Graphite.....	Above 3000°C.
Zirconium oxide.....	2700°C.

V. TEMPERATURE COEFFICIENTS OF VOLUME EXPANSION

Air.....	0-100°C.	0.0036728
Mercury.....	0-100°C.	0.00018138
Glass (soft).....	0-100°C.	0.000025
Quartz (fused).....	0-100°C.	0.00000054
Platinum.....	20°C.	0.0000267
	5-10°C.	0.0000053
	10-20°C.	0.0000150
Water	20-40°C.	0.0000362
	40-60°C.	0.0000458
	60-80°C.	0.0000587

VI. TEMPERATURE CONVERSION TABLE
(American Society for Steel Treating)

C.°	0	10	20	30	40	50	60	70	80	90		
-200	F -328	F -346	F -364	F -382	F -400	F -418	F -436	F -454	F -472	F -490	Interpolation. Columns	
-100	-143	-166	-184	-202	-220	-238	-256	-274	-292	-310		
-0	+32	+14	-4	-22	-40	-58	-76	-94	-112	-130		
0	32	50	68	86	104	122	140	158	176	194		
100	212	230	248	266	284	302	320	338	356	374	C.°	F.°
200	392	410	428	446	464	482	500	518	536	554	1	1.8
300	572	590	608	626	644	662	680	698	716	734	2	3.6
400	752	770	788	806	824	842	860	878	896	914	3	5.4
500	932	950	968	986	1004	1022	1040	1058	1076	1094	4	7.2
600	1112	1130	1148	1166	1184	1202	1220	1238	1256	1274	5	9.0
700	1292	1310	1328	1346	1364	1382	1400	1418	1436	1454	6	10.8
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634	7	12.6
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814	8	14.4
1000	1832	1850	1868	1886	1904	1922	1940	1958	1976	1994	9	16.2
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174	10	18.0
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354		
1300	2372	2390	2408	2426	2444	2462	2480	2498	2516	2534		
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714		
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894		
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074		
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254	F.°	C.°
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3434	1	5.6
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614	2	1.11
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794	3	1.67
2100	3812	3830	3848	3866	3884	3902	3920	3938	3956	3974	4	2.22
2200	3992	4010	4028	4046	4064	4082	4100	4118	4136	4154	5	2.78
2300	4172	4190	4208	4226	4244	4262	4280	4298	4316	4334	6	3.33
2400	4352	4370	4388	4406	4424	4442	4460	4478	4496	4514	7	3.89
2500	4532	4550	4568	4586	4604	4622	4640	4658	4676	4694	8	4.44
2600	4712	4730	4748	4766	4784	4802	4820	4838	4856	4874	9	5.00
2700	4892	4910	4928	4946	4964	4982	5000	5018	5036	5054	10	5.56
2800	5072	5090	5108	5126	5144	5162	5180	5198	5216	5234	11	6.11
2900	5252	5270	5288	5306	5324	5342	5360	5378	5396	5414	12	6.67
3000	5432	5450	5468	5486	5504	5522	5540	5558	5576	5594	13	7.22
3100	5612	5630	5648	5666	5684	5702	5720	5738	5756	5774	14	7.78
3200	5792	5810	5828	5846	5864	5882	5900	5918	5936	5954	15	8.33
3300	5972	5990	6008	6026	6044	6062	6080	6098	6116	6134	16	8.89
3400	6152	6170	6188	6206	6224	6242	6260	6278	6296	6314	17	9.44
3500	6332	6350	6368	6386	6404	6422	6440	6458	6476	6494	18	10.00
3600	6512	6530	6548	6566	6584	6602	6620	6638	6656	6674		
3700	6692	6710	6728	6746	6764	6782	6800	6818	6836	6854		
3800	6872	6890	6908	6926	6944	6962	6980	6998	7016	7034		
3900	7052	7070	7088	7106	7124	7142	7160	7178	7196	7214		
C.°	0	10	20	30	40	50	60	70	80	90		

VII.—TEMPERATURE-E.M.F. TABLE FOR PLATINUM *versus* PLATINUM + 10 PER CENT RHODIUM THERMOCOUPLE
(*Leeds and Northrup Company*)

Degrees Centigrade	Degrees Centigrade										Cold junction 0°C.						Degrees Centigrade
	0°	100°	200°	300°	400°	500°	600°	700°	800°	900°	Millivolts						
											1000°	1100°	1200°	1300°	1400°	1500°	
0	0	0.643	1.43	2.31	3.24	4.22	5.24	6.26	7.33	8.43	9.57	10.74	11.93	13.13	14.33	15.55	0
2	0.012	0.658	1.45	2.33	3.26	4.24	5.24	6.28	7.35	8.45	9.59	10.76	11.95	13.15	14.35	15.57	2
4	0.024	0.673	1.46	2.35	3.28	4.26	5.26	6.30	7.37	8.48	9.62	10.79	11.98	13.18	14.38	15.60	4
6	0.036	0.688	1.48	2.37	3.30	4.28	5.28	6.32	7.39	8.50	9.64	10.81	12.00	13.20	14.40	15.62	6
8	0.048	0.703	1.50	2.38	3.32	4.30	5.30	6.34	7.42	8.52	9.66	10.83	12.03	13.23	14.43	15.65	8
10	0.060	0.719	1.52	2.40	3.34	4.32	5.32	6.37	7.44	8.54	9.69	10.86	12.05	13.25	14.45	15.67	10
12	0.072	0.734	1.53	2.42	3.36	4.34	5.34	6.39	7.46	8.57	9.71	10.88	12.07	13.27	14.48	15.69	12
14	0.084	0.749	1.55	2.44	3.38	4.36	5.36	6.41	7.48	8.59	9.73	10.91	12.10	13.30	14.50	15.72	14
16	0.096	0.764	1.57	2.46	3.40	4.38	5.38	6.43	7.51	8.61	9.76	10.93	12.12	13.32	14.53	15.74	16
18	0.107	0.779	1.59	2.48	3.42	4.39	5.41	6.45	7.53	8.63	9.78	10.95	12.15	13.35	14.55	15.77	18
20	0.119	0.795	1.60	2.50	3.44	4.41	5.43	6.47	7.55	8.66	9.80	10.98	12.17	13.37	14.57	15.79	20
22	0.131	0.810	1.62	2.51	3.45	4.43	5.45	6.49	7.57	8.68	9.82	11.00	12.19	13.39	14.60	15.81	22
24	0.143	0.825	1.64	2.53	3.47	4.45	5.47	6.51	7.59	8.70	9.85	11.02	12.22	13.42	14.62	15.84	24
26	0.155	0.840	1.66	2.55	3.49	4.47	5.49	6.53	7.61	8.73	9.87	11.05	12.24	13.44	14.65	15.86	26
28	0.167	0.855	1.67	2.57	3.51	4.49	5.51	6.56	7.64	8.75	9.89	11.07	12.27	13.47	14.67	15.89	28
30	0.179	0.871	1.69	2.59	3.53	4.51	5.53	6.58	7.66	8.77	9.92	11.09	12.29	13.49	14.70	15.91	30
32	0.191	0.886	1.71	2.61	3.55	4.53	5.55	6.60	7.68	8.80	9.94	11.12	12.31	13.51	14.72	15.93	32
34	0.203	0.901	1.72	2.62	3.57	4.55	5.57	6.62	7.70	8.82	9.96	11.14	12.34	13.54	14.74	15.96	34
36	0.215	0.916	1.74	2.64	3.59	4.57	5.59	6.64	7.72	8.84	9.99	11.16	12.36	13.56	14.77	15.98	36
38	0.226	0.931	1.76	2.66	3.61	4.59	5.61	6.66	7.75	8.86	10.01	11.19	12.39	13.59	14.79	16.01	38
40	0.238	0.947	1.78	2.68	3.63	4.61	5.63	6.68	7.77	8.89	10.03	11.21	12.41	13.61	14.82	16.03	40
42	0.250	0.962	1.79	2.70	3.65	4.63	5.65	6.70	7.79	8.91	10.06	11.24	12.43	13.63	14.84	16.05	42
44	0.262	0.977	1.81	2.72	3.67	4.65	5.67	6.73	7.81	8.93	10.08	11.26	12.46	13.66	14.87	16.08	44
46	0.274	0.992	1.83	2.73	3.69	4.67	5.69	6.75	7.83	8.95	10.10	11.28	12.48	13.68	14.89	16.10	46
48	0.286	1.01	1.85	2.75	3.71	4.69	5.71	6.77	7.86	8.98	10.13	11.31	12.51	13.71	14.92	16.13	48
50	0.298	1.02	1.86	2.77	3.72	4.71	5.74	6.79	7.88	9.00	10.15	11.33	12.53	13.73	14.94	16.15	50
52	0.312	1.04	1.88	2.79	3.74	4.73	5.76	6.81	7.90	9.02	10.17	11.35	12.55	13.75	14.96	16.17	52
54	0.326	1.05	1.90	2.81	3.76	4.75	5.78	6.83	7.92	9.05	10.20	11.38	12.58	13.78	14.99	16.20	54
56	0.340	1.07	1.92	2.83	3.78	4.77	5.80	6.86	7.94	9.07	10.22	11.40	12.60	13.80	15.01	16.22	56
58	0.354	1.09	1.94	2.85	3.80	4.79	5.82	6.88	7.97	9.09	10.24	11.43	12.63	13.83	15.04	16.25	58
60	0.367	1.10	1.95	2.87	3.82	4.81	5.84	6.90	7.99	9.11	10.27	11.45	12.65	13.85	15.06	16.27	60
62	0.381	1.12	1.97	2.89	3.84	4.84	5.86	6.92	8.01	9.14	10.29	11.47	12.67	13.87	15.09	16.29	62

64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98	100	Millivolts per degree
0.395	1.14	1.99	2.90	3.86	4.86	5.88	6.94	8.03	9.16	10.32	11.50	12.70	13.90	15.11	16.32	16.32	64		
0.409	1.15	2.01	2.92	3.88	4.88	5.90	6.96	8.05	9.18	10.34	11.52	12.72	13.92	15.14	16.34	16.34	66		
0.423	1.17	2.03	2.94	3.90	4.90	5.92	6.98	8.08	9.20	10.36	11.55	12.75	13.95	15.16	16.37	16.37	68		
0.436	1.19	2.04	2.96	3.92	4.92	5.95	7.01	8.10	9.23	10.39	11.57	12.77	13.97	15.18	16.39	16.39	70		
0.450	1.20	2.06	2.98	3.94	4.94	5.97	7.03	8.12	9.25	10.41	11.59	12.79	13.99	15.21	16.41	16.41	72		
0.464	1.22	2.08	3.00	3.96	4.96	5.99	7.05	8.14	9.27	10.43	11.62	12.82	14.02	15.23	16.44	16.44	74		
0.478	1.23	2.10	3.02	3.98	4.98	6.01	7.07	8.17	9.30	10.46	11.64	12.84	14.04	15.26	16.46	16.46	76		
0.492	1.25	2.12	3.04	4.00	5.00	6.03	7.09	8.19	9.32	10.48	11.67	12.87	14.07	15.28	16.49	16.49	78		
0.505	1.27	2.13	3.06	4.02	5.02	6.05	7.11	8.21	9.34	10.50	11.69	12.89	14.09	15.31	16.51	16.51	80		
0.519	1.28	2.15	3.07	4.04	5.04	6.07	7.13	8.23	9.37	10.53	11.71	12.91	14.11	15.33	16.53	16.53	82		
0.533	1.30	2.17	3.09	4.06	5.06	6.09	7.16	8.25	9.39	10.55	11.74	12.94	14.14	15.35	16.56	16.56	84		
0.547	1.32	2.19	3.11	4.08	5.08	6.11	7.18	8.28	9.41	10.57	11.76	12.96	14.16	15.38	16.58	16.58	86		
0.561	1.33	2.21	3.13	4.10	5.10	6.13	7.20	8.30	9.43	10.60	11.79	12.99	14.19	15.40	16.61	16.61	88		
0.574	1.35	2.22	3.15	4.12	5.12	6.15	7.22	8.32	9.46	10.62	11.81	13.01	14.21	15.43	16.63	16.63	90		
0.588	1.37	2.24	3.17	4.14	5.14	6.18	7.24	8.34	9.48	10.65	11.83	13.03	14.23	15.45	16.65	16.65	92		
0.602	1.38	2.26	3.19	4.16	5.16	6.20	7.26	8.37	9.50	10.67	11.86	13.06	14.26	15.48	16.68	16.68	94		
0.616	1.40	2.28	3.21	4.18	5.18	6.22	7.29	8.39	9.52	10.69	11.88	13.08	14.28	15.50	16.70	16.70	96		
0.630	1.41	2.29	3.23	4.20	5.20	6.24	7.31	8.41	9.55	10.72	11.91	13.11	14.31	15.53	16.73	16.73	98		
0.643	1.43	2.31	3.24	4.22	5.22	6.26	7.33	8.43	9.57	10.74	11.93	13.13	14.33	15.55	16.75	16.75	100		
0.0064	0.0079	0.0088	0.0098	0.0098	0.0100	0.0104	0.0107	0.0110	0.0114	0.0117	0.0119	0.012	0.0122	0.0122	0.012	0.012	Millivolts per degree		

VIII. TEMPERATURE-E.M.F. TABLE FOR IRON-CONSTANTAN THERMOCOUPLE
(*Leeds and Northrup Company*)

Degrees Centigrade	Degrees Centigrade						Cold junction 0°C.						Degrees Centigrade
	0°	100°	200°	300°	400°	500°	Millivolts						
							600°	700°	800°	900°	1000°		
0	0	5.28	10.78	16.30	21.82	27.39	33.16	39.19	45.48	51.82	58.16	0	
2	0.10	5.39	10.89	16.41	21.93	27.50	33.28	39.32	45.61	51.95	58.29	2	
4	0.21	5.50	11.00	16.52	22.04	27.62	33.40	39.44	45.73	52.07	58.41	4	
6	0.31	5.61	11.11	16.63	22.15	27.73	33.52	39.57	45.86	52.20	58.54	6	
8	0.42	5.72	11.22	16.74	22.26	27.84	33.64	39.69	45.99	52.33	58.67	8	
10	0.52	5.83	11.33	16.85	22.37	27.96	33.75	39.82	46.11	52.45	58.79	10	
12	0.62	5.94	11.44	16.96	22.48	28.08	33.87	39.94	46.24	52.58	58.92	12	
14	0.73	6.05	11.55	17.07	22.59	28.19	33.99	40.07	46.37	52.71	59.05	14	
16	0.83	6.16	11.66	17.18	22.70	28.31	34.11	40.19	46.49	52.83	59.17	16	
18	0.94	6.27	11.77	17.29	22.81	28.42	34.23	40.32	46.62	52.96	59.30	18	
20	1.04	6.38	11.88	17.40	22.92	28.53	34.35	40.44	46.75	53.09	59.43	20	
22	1.14	6.49	11.99	17.51	23.03	28.65	34.47	40.57	46.87	53.21	59.55	22	
24	1.25	6.60	12.10	17.62	23.14	28.76	34.59	40.69	47.00	53.34	59.68	24	
26	1.35	6.70	12.22	17.74	23.26	28.88	34.70	40.82	47.13	53.47	59.81	26	
28	1.46	6.81	12.33	17.85	23.37	28.99	34.82	40.94	47.26	53.60	59.94	28	
30	1.56	6.92	12.44	17.96	23.48	29.11	34.94	41.07	47.38	53.72	60.06	30	
32	1.66	7.03	12.55	18.07	23.59	29.22	35.06	41.19	47.51	53.85	60.19	32	
34	1.77	7.14	12.66	18.18	23.70	29.33	35.18	41.32	47.64	53.98	60.32	34	
36	1.87	7.25	12.77	18.29	23.81	29.45	35.30	41.44	47.76	54.10	60.44	36	
38	1.98	7.36	12.88	18.40	23.92	29.56	35.42	41.57	47.89	54.23	60.57	38	
40	2.08	7.47	12.99	18.51	24.03	29.68	35.54	41.69	48.02	54.36	60.70	40	
42	2.18	7.58	13.10	18.62	24.14	29.79	35.65	41.82	48.14	54.48	60.82	42	
44	2.29	7.69	13.21	18.73	24.25	29.91	35.77	41.94	48.27	54.61	60.95	44	
46	2.39	7.80	13.32	18.84	24.36	30.02	35.89	42.07	48.40	54.74	61.08	46	
48	2.50	7.91	13.43	18.95	24.47	30.14	36.01	42.19	48.52	54.86	61.20	48	
50	2.60	8.02	13.54	19.06	24.58	30.25	36.13	42.32	48.65	54.99	61.33	50	
52	2.71	8.13	13.65	19.17	24.69	30.37	36.25	42.45	48.78	55.12	61.46	52	
54	2.81	8.24	13.76	19.28	24.80	30.48	36.37	42.57	48.90	55.24	61.58	54	
56	2.92	8.35	13.87	19.39	24.92	30.60	36.50	42.70	49.03	55.37	61.71	56	
58	3.03	8.46	13.98	19.50	25.03	30.71	36.62	42.83	49.16	55.50	61.84	58	
60	3.14	8.57	14.09	19.61	25.14	30.83	36.74	42.95	49.28	55.62	61.96	60	

62	3.24	8.63	14.20	19.72	25.25	30.95	36.86	43.08	49.41	55.75	62.09	62
64	3.35	8.79	14.31	19.83	25.37	31.06	36.99	43.20	49.54	55.88	62.22	64
66	3.46	8.90	14.42	19.94	25.48	31.18	37.11	43.33	49.66	56.00	62.34	66
68	3.56	9.01	14.53	20.05	25.59	31.30	37.23	43.46	49.79	56.13	62.47	68
70	3.67	9.12	14.64	20.16	25.70	31.41	37.35	43.58	49.92	56.26	62.60	70
72	3.78	9.23	14.75	20.27	25.82	31.53	37.48	43.71	50.04	56.38	62.72	72
74	3.89	9.34	14.86	20.38	25.93	31.65	37.60	43.84	50.17	56.51	62.85	74
76	3.99	9.45	14.98	20.49	26.04	31.76	37.72	43.96	50.30	56.64	62.98	76
78	4.10	9.57	15.09	20.61	26.15	31.88	37.84	44.09	50.43	56.77	63.10	78
80	4.21	9.68	15.20	20.72	26.27	32.00	37.97	44.22	50.55	56.89	63.23	80
82	4.31	9.79	15.31	20.83	26.38	32.11	38.09	44.34	50.68	57.02	63.36	82
84	4.42	9.90	15.42	20.94	26.49	32.23	38.21	44.47	50.80	57.16	63.49	84
86	4.53	10.01	15.53	21.05	26.60	32.35	38.33	44.60	50.92	57.27	63.61	86
88	4.64	10.12	15.64	21.16	26.72	32.46	38.46	44.72	51.06	57.40	63.74	88
90	4.74	10.23	15.75	21.27	26.83	32.58	38.58	44.85	51.19	57.53	63.87	90
92	4.85	10.34	15.86	21.38	26.94	32.69	38.70	44.97	51.31	57.65	63.99	92
94	4.96	10.45	15.97	21.49	27.05	32.81	38.82	45.10	51.44	57.78	64.12	94
96	5.06	10.56	16.08	21.60	27.17	32.93	38.94	45.23	51.57	57.91	64.25	96
98	5.17	10.67	16.19	21.71	27.28	33.04	39.07	45.35	51.69	58.03	64.37	98
100	5.28	10.78	16.30	21.82	27.39	33.16	39.19	45.48	51.82	58.16	64.50	100
Millivolts per degrees Centi- grade	0.0528	0.055	0.0552	0.0552	0.0557	0.0577	0.0603	0.0629	0.0634	0.0634	0.0634	

IX. TEMPERATURE-E.M.F. TABLE FOR CHROMEL-ALUMEL THERMOCOUPLE
 (Leeds and Northrup Company)

Degrees Centigrade															Degrees Centigrade															Cold junction 0°C.																																							
0°					100°					200°					300°					400°					500°					600°					700°					800°					900°					1000°					1100°					1200°					1300°				
Millivolts																																																																					
0	0	4.17	8.27	12.36	16.46	20.73	24.97	29.11	33.25	37.36	41.27	45.05	48.83	52.49	0.08	0.16	0.24	0.32	0.39	0.47	0.55	0.62	0.70	0.77	0.85	0.92	1.00	1.08	1.15	1.24	1.33	1.42	1.51	1.59	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46																									
2	0.08	4.25	8.35	12.44	16.55	20.81	25.05	29.19	33.33	37.44	41.35	45.13	48.91	52.56	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40																										
4	0.16	4.34	8.43	12.53	16.63	20.90	25.13	29.28	33.42	37.52	41.42	45.20	48.98	52.63	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40	2.48	2.56																									
6	0.24	4.42	8.51	12.61	16.72	20.98	25.22	29.36	33.50	37.60	41.50	45.28	49.06	52.70	0.32	0.40	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40	2.48	2.56	2.64																									
8	0.32	4.50	8.59	12.69	16.80	21.06	25.30	29.44	33.58	37.68	41.57	45.35	49.13	52.77	0.40	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40	2.48	2.56	2.64																										
10	0.39	4.59	8.68	12.78	16.89	21.15	25.39	29.53	33.67	37.77	41.65	45.43	49.21	52.85	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40	2.48	2.56	2.64																											
12	0.47	4.68	8.76	12.86	16.98	21.23	25.47	29.61	33.75	37.85	41.73	45.51	49.28	52.92	0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44	1.52	1.60	1.68	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.32	2.40	2.48	2.56	2.64																												
14	0.55	4.76	8.84	12.94	17.06	21.31	25.56	29.70	33.84	37.93	41.80	45.58	49.36	53.00	0.62	0.70	0.78	0.86	0.94	1.02	1.10	1.18	1.26	1.34	1.42	1.50	1.58	1.66	1.74	1.82	1.90	1.98	2.06	2.14	2.22	2.30	2.38	2.46	2.54	2.62																													
16	0.62	4.85	8.92	13.02	17.15	21.40	25.64	29.79	33.92	38.01	41.88	45.66	49.43	53.06	0.70	0.78	0.86	0.94	1.02	1.10	1.18	1.26	1.34	1.42	1.50	1.58	1.66	1.74	1.82	1.90	1.98	2.06	2.14	2.22	2.30	2.38	2.46	2.54	2.62	2.70																													
18	0.70	4.93	9.00	13.10	17.23	21.48	25.72	29.87	34.00	38.09	41.95	45.73	49.51	53.13	0.78	0.86	0.94	1.02	1.10	1.18	1.26	1.34	1.42	1.50	1.58	1.66	1.74	1.82	1.90	1.98	2.06	2.14	2.22	2.30	2.38	2.46	2.54	2.62	2.70	2.78																													
20	0.77	5.02	9.09	13.18	17.32	21.57	25.81	29.95	34.09	38.18	42.03	45.81	49.58	53.21	0.85	0.93	1.01	1.09	1.17	1.25	1.33	1.41	1.49	1.57	1.65	1.73	1.81	1.89	1.97	2.05	2.13	2.21	2.29	2.37	2.45	2.53	2.61	2.69	2.77																														
22	0.85	5.10	9.17	13.26	17.41	21.65	25.89	30.03	34.17	38.26	42.10	45.88	49.65	53.29	0.92	1.00	1.08	1.16	1.24	1.32	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96	2.04	2.12	2.20	2.28	2.36	2.44	2.52	2.60	2.68	2.76	2.84																														
24	0.92	5.18	9.25	13.34	17.49	21.73	25.97	30.11	34.25	38.34	42.18	45.96	49.72	53.36	1.00	1.08	1.16	1.24	1.32	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96	2.04	2.12	2.20	2.28	2.36	2.44	2.52	2.60	2.68	2.76	2.84	2.92																														
26	1.00	5.26	9.33	13.42	17.58	21.82	26.06	30.19	34.34	38.42	42.25	46.03	49.79	53.44	1.08	1.16	1.24	1.32	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96	2.04	2.12	2.20	2.28	2.36	2.44	2.52	2.60	2.68	2.76	2.84	2.92	3.00																														
28	1.08	5.34	9.41	13.50	17.66	21.90	26.14	30.27	34.42	38.50	42.33	46.11	49.86	53.51	1.15	1.24	1.33	1.42	1.51	1.59	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18																															
30	1.15	5.43	9.50	13.58	17.75	21.98	26.22	30.36	34.51	38.57	42.40	46.18	49.94	53.59	1.24	1.33	1.42	1.51	1.60	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27																															
32	1.24	5.51	9.58	13.66	17.83	22.06	26.30	30.44	34.59	38.65	42.48	46.26	50.02	53.66	1.33	1.42	1.51	1.60	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36																															
34	1.33	5.59	9.66	13.74	17.91	22.14	26.39	30.52	34.67	38.73	42.56	46.34	50.09	53.74	1.42	1.51	1.60	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45																															
36	1.42	5.67	9.74	13.82	18.00	22.23	26.47	30.60	34.75	38.81	42.64	46.42	50.17	53.81	1.51	1.60	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54																															
38	1.51	5.75	9.82	13.90	18.08	22.31	26.55	30.68	34.83	38.89	42.72	46.50	50.24	53.88	1.59	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63																															
40	1.59	5.84	9.90	13.98	18.17	22.39	26.63	30.77	34.90	38.97	42.79	46.57	50.32	53.96	1.68	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72																															
42	1.68	5.92	9.98	14.06	18.26	22.48	26.71	30.85	34.98	39.05	42.86	46.64	50.39	54.03	1.76	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81																															
44	1.76	6.01	10.06	14.14	18.34	22.56	26.79	30.93	35.06	39.12	42.94	46.72	50.46	54.10	1.85	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90																															
46	1.85	6.09	10.14	14.22	18.43	22.65	26.96	31.01	35.15	39.20	43.01	46.79	50.53	54.17	1.93	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00																															
48	1.93	6.17	10.22	14.30	18.51	22.73	26.96	31.09	35.23	39.27	43.09	46.87	50.60	54.24	2.02	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09																															
50	2.02	6.26	10.31	14.39	18.60	22.82	27.04	31.18	35.32	39.35	43.16	46.94	50.68	54.32	2.11	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18																															
52	2.11	6.34	10.39	14.47	18.69	22.91	27.12	31.26	35.40	39.43	43.24	47.02	50.76	54.39	2.20	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18	4.27																															
54	2.20	6.42	10.47	14.55	18.78	23.00	27.21	31.34	35.48	39.51	43.31	47.09	50.83	54.46	2.28	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18	4.27	4.36																															
56	2.28	6.50	10.55	14.63	18.86	23.08	27.29	31.43	35.57	39.59	43.39	47.17	50.91	54.53	2.37	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18	4.27	4.36	4.45																															
58	2.37	6.58	10.63	14.71	18.95	23.17	27.37	31.51	35.65	39.67	43.46	47.24	50.98	54.60	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18	4.27	4.36	4.45	4.54																															
60	2.46	6.66	10.72	14.79	19.04	23.26	27.46	31.60	35.74	39.74	43.54	47.32	51.06	54.68	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.18	3.27	3.36	3.45	3.54	3.63	3.72	3.81	3.90	4.00	4.09	4.18	4.27	4.36	4.45	4.54	4.63																															

62	2.55	6.74	10.80	14.87	19.13	23.35	27.54	31.68	35.82	39.82	43.62	47.40	51.13	54.75
64	2.64	6.82	10.88	14.95	19.22	23.44	27.63	31.77	35.90	39.90	43.69	47.47	51.20	54.82
66	2.73	6.91	10.97	15.04	19.31	23.52	27.71	31.85	35.99	39.98	43.77	47.55	51.27	54.89
68	2.82	6.99	11.05	15.12	19.39	23.61	27.79	31.93	36.07	40.06	43.84	47.62	51.34	54.96
70	2.90	7.08	11.14	15.21	19.48	23.70	27.88	32.02	36.16	40.13	43.92	47.70	51.42	55.04
72	2.99	7.16	11.22	15.29	19.57	23.79	27.96	32.10	36.24	40.21	43.99	47.77	51.49	55.11
74	3.07	7.24	11.30	15.37	19.65	23.87	28.04	32.18	36.32	40.28	44.07	47.85	51.56	55.18
76	3.16	7.32	11.38	15.46	19.74	23.96	28.13	32.26	36.40	40.36	44.14	47.92	51.63	55.25
78	3.24	7.40	11.46	15.54	19.82	24.04	28.21	32.34	36.48	40.43	44.22	48.00	51.70	55.32
80	3.33	7.48	11.54	15.63	19.91	24.13	28.29	32.43	36.56	40.51	44.29	48.07	51.76	55.40
82	3.41	7.56	11.62	15.71	19.99	24.21	28.37	32.51	36.64	40.59	44.37	48.15	51.84	55.47
84	3.50	7.64	11.70	15.79	20.07	24.30	28.45	32.59	36.72	40.67	44.45	48.23	51.91	55.54
86	3.58	7.72	11.78	15.87	20.15	24.38	28.53	32.67	36.80	40.75	44.53	48.31	51.99	55.61
88	3.67	7.80	11.86	15.95	20.23	24.47	28.61	32.75	36.88	40.83	44.61	48.39	52.06	55.68
90	3.75	7.88	11.95	16.04	20.32	24.55	28.70	32.84	36.96	40.90	44.68	48.46	52.14	55.76
92	3.83	7.96	12.03	16.12	20.40	24.63	28.78	32.92	37.04	40.97	44.75	48.53	52.21	55.83
94	3.92	8.04	12.11	16.21	20.48	24.72	28.86	33.00	37.12	41.05	44.83	48.61	52.28	55.90
96	4.00	8.12	12.19	16.29	20.56	24.80	28.94	33.08	37.20	41.12	44.90	48.68	52.35	55.97
98	4.08	8.20	12.27	16.38	20.64	24.89	29.02	33.16	37.28	41.20	44.98	48.76	52.42	56.04
100	4.17	8.27	12.36	16.46	20.73	24.97	29.11	33.25	37.36	41.27	45.05	48.83	52.49	56.12
Millivolts per degrees Centigrade	0.0417	0.041	0.0409	0.041	0.0427	0.0424	0.0414	0.0414	0.0411	0.0391	0.0378	0.0378	0.0366	0.0363

X. TEMPERATURE-E.M.F. TABLE FOR COPPER-CONSTANTAN THERMOCOUPLE
(Leeds and Northrup Company)

Degrees Centigrade	Degrees Centigrade					Cold junction 0°C.					Degrees Centigrade
	0	10	20	30	40	50	60	70	80	90	
	Millivolts										
0	0.0	0.40	0.80	1.20	1.61	2.03	2.46	2.89	3.33	3.78	0
1	0.04	0.44	0.84	1.24	1.65	2.07	2.50	2.93	3.37	3.83	1
2	0.08	0.48	0.88	1.28	1.69	2.12	2.55	2.98	3.42	3.87	2
3	0.12	0.52	0.92	1.32	1.74	2.16	2.59	3.02	3.46	3.92	3
4	0.16	0.56	0.96	1.36	1.78	2.20	2.63	3.07	3.51	3.97	4
5	0.20	0.60	1.00	1.40	1.82	2.24	2.67	3.11	3.55	4.01	5
6	0.24	0.64	1.04	1.45	1.86	2.29	2.72	3.15	3.60	4.06	6
7	0.28	0.68	1.08	1.49	1.90	2.33	2.76	3.20	3.64	4.10	7
8	0.32	0.72	1.12	1.53	1.95	2.37	2.80	3.24	3.69	4.15	8
9	0.36	0.76	1.16	1.57	1.99	2.42	2.85	3.29	3.73	4.19	9
10	0.40	0.80	1.20	1.61	2.03	2.46	2.89	3.33	3.78	4.24	10
Millivolts per degrees Centigrade	0.04	0.04	0.04	0.041	0.042	0.043	0.043	0.044	0.045	0.046	

Degrees Centigrade	100	110	120	130	140	150	160	170	180	190	Degrees Centigrade
	Millivolts										
	Millivolts										
0	4.24	4.71	5.17	5.63	6.10	6.58	7.06	7.56	8.06	8.56	0
1	4.29	4.75	5.21	5.67	6.14	6.62	7.11	7.61	8.11	8.61	1
2	4.33	4.80	5.26	5.72	6.19	6.67	7.16	7.66	8.16	8.66	2
3	4.38	4.84	5.31	5.77	6.24	6.72	7.21	7.71	8.21	8.71	3
4	4.43	4.89	5.35	5.82	6.29	6.77	7.26	7.76	8.26	8.76	4
5	4.47	4.94	5.40	5.86	6.34	6.82	7.31	7.81	8.31	8.81	5
6	4.52	4.98	5.44	5.91	6.38	6.86	7.36	7.86	8.36	8.86	6
7	4.57	5.03	5.49	5.96	6.43	6.91	7.41	7.91	8.41	8.91	7
8	4.61	5.08	5.54	6.00	6.48	6.96	7.46	7.96	8.46	8.96	8
9	4.66	5.12	5.58	6.05	6.53	7.01	7.51	8.01	8.51	9.01	9
10	4.71	5.17	5.63	6.10	6.58	7.06	7.56	8.06	8.56	9.06	10
Millivolt per degrees Centigrade	0.047	0.046	0.046	0.047	0.048	0.048	0.050	0.050	0.050	0.050	

Millivolts per degrees Centigrade	200	210	220	230	240	250	260	270	280	290	Degrees Centigrade
	Millivolts										
	Millivolts										
0	9.06	9.56	10.06	10.57	11.09	11.62	12.16	12.71	13.27	13.84	0
1	9.11	9.61	10.11	10.62	11.14	11.67	12.21	12.76	13.32	13.89	1
2	9.16	9.66	10.16	10.67	11.19	11.72	12.27	12.82	13.38	13.95	2
3	9.21	9.71	10.21	10.72	11.24	11.78	12.32	12.87	13.44	14.01	3
4	9.26	9.76	10.26	10.77	11.30	11.83	12.38	12.93	13.49	14.07	4
5	9.31	9.81	10.31	10.83	11.35	11.89	12.43	12.99	13.55	14.13	5
6	9.36	9.86	10.36	10.88	11.40	11.94	12.49	13.04	13.61	14.18	6
7	9.41	9.91	10.41	10.93	11.46	11.99	12.54	13.10	13.66	14.24	7
8	9.46	9.96	10.46	10.98	11.51	12.05	12.60	13.15	13.72	14.30	8
9	9.51	10.01	10.51	11.03	11.56	12.10	12.65	13.21	13.78	14.36	9
10	9.56	10.06	10.57	11.09	11.62	12.16	12.71	13.27	13.84	14.42	10
Millivolts per degrees Centigrade	0.050	0.050	0.051	0.052	0.053	0.054	0.055	0.056	0.057	0.058	

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